

# Self-field and in-field performance enhancement for coated conductors

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Steve Foltyn, Leonardo Civale

Haiyan Wang, Boris Maiorov, Quanxi Jia, Paul Arendt,  
Judith Driscoll\*, Jason Mantei\*\*, Yuan Li, Yuan Lin, Marty Maley

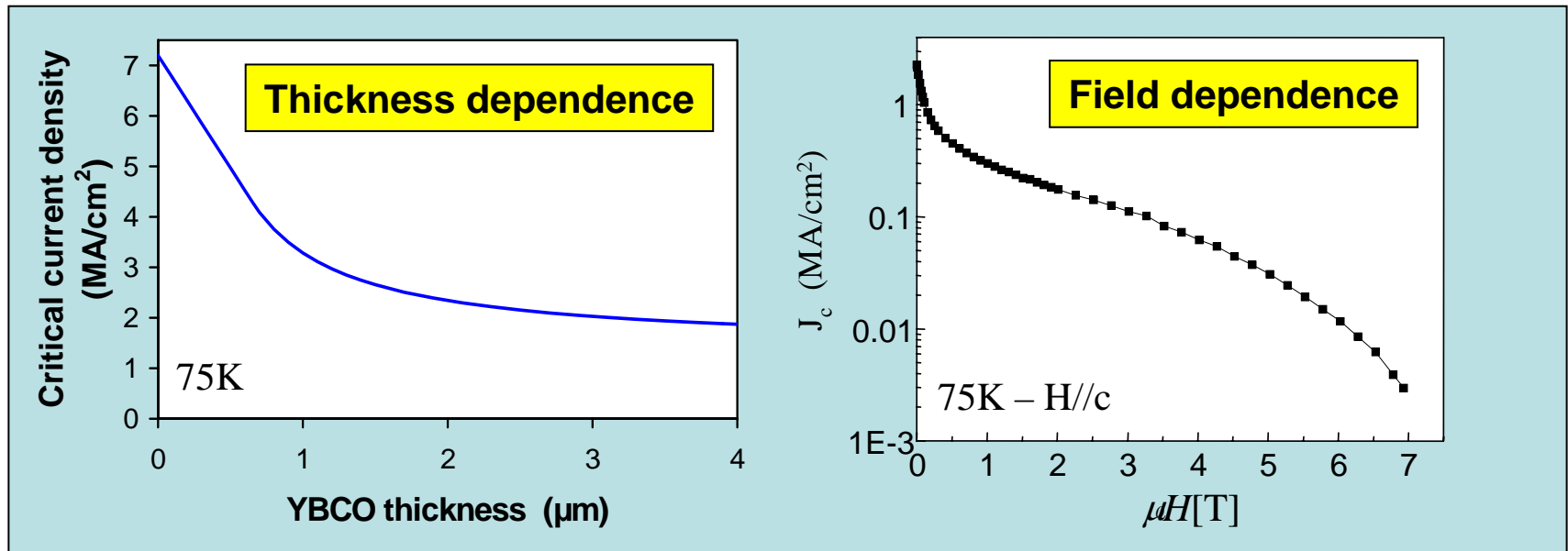
*Superconductivity Technology Center  
Los Alamos National Laboratory  
and*

*\*University of Cambridge*

*\*\*University of Wisconsin-Madison*

Project cost: \$900k

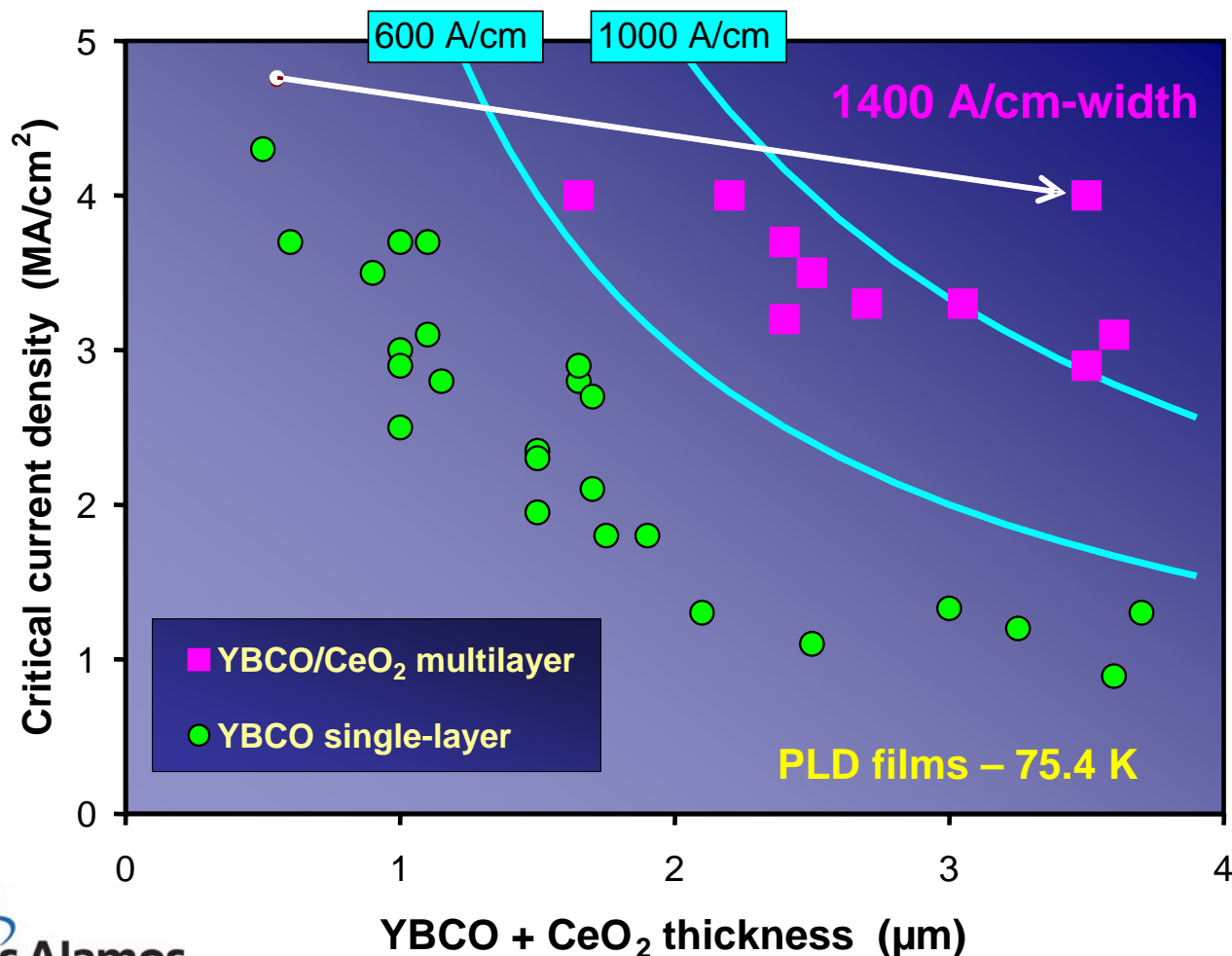
Although many problems have been solved,\* there are still two important areas that require improvement



\*Examples of solved problems:

- ▶ The self field  $J_c$  of very thin films, 7 MA/cm<sup>2</sup>, is ~ 10% of depairing current density – further improvement is unlikely.
- ▶ Performance of IBAD MgO-based coated conductors is not limited by grain boundaries –  $J_c$  is the same as for single-crystal substrates.

# Last year we showed that multilayer coated conductors have $J_c$ values above 1000 A/cm-width

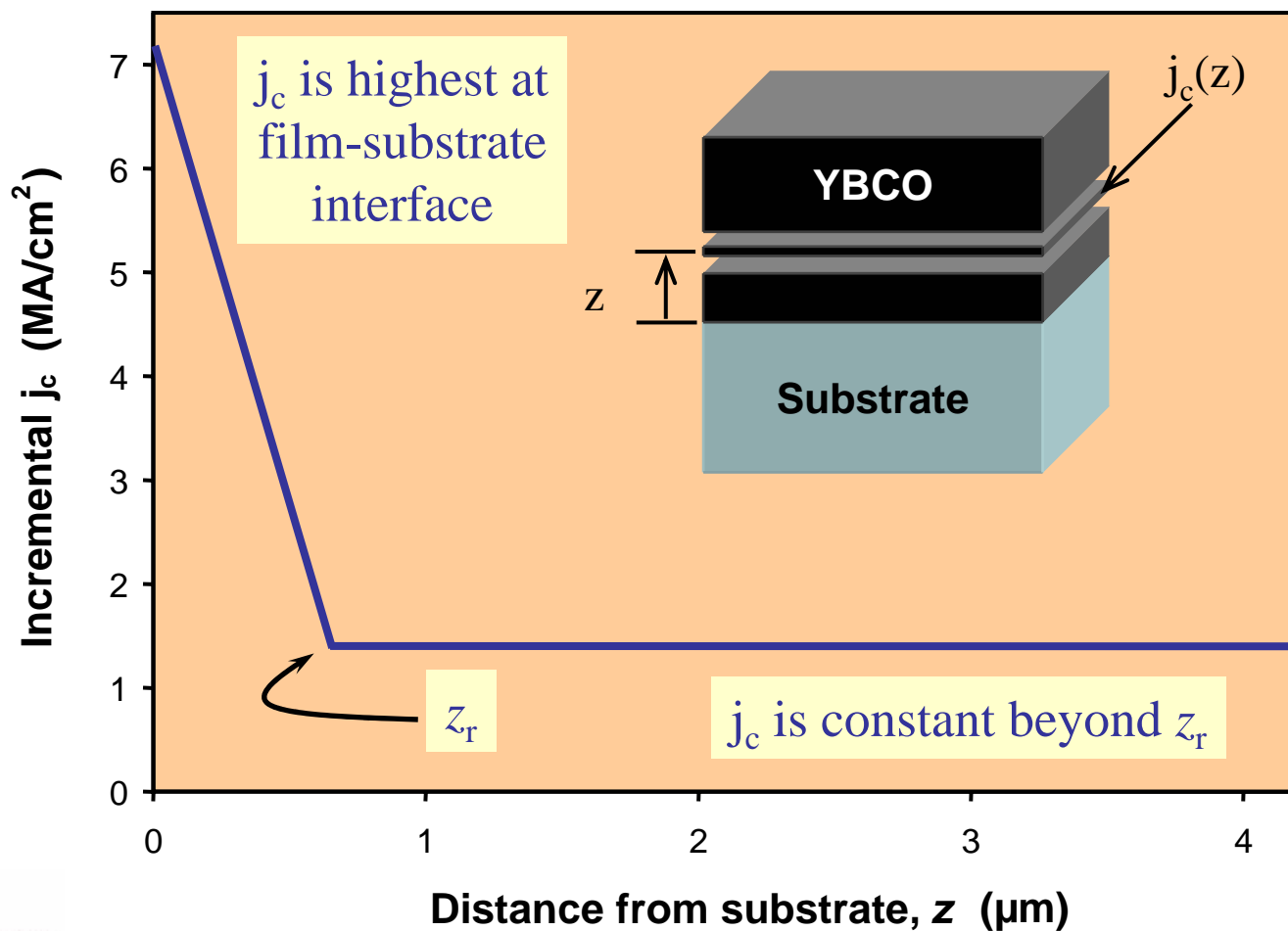


## Arrow

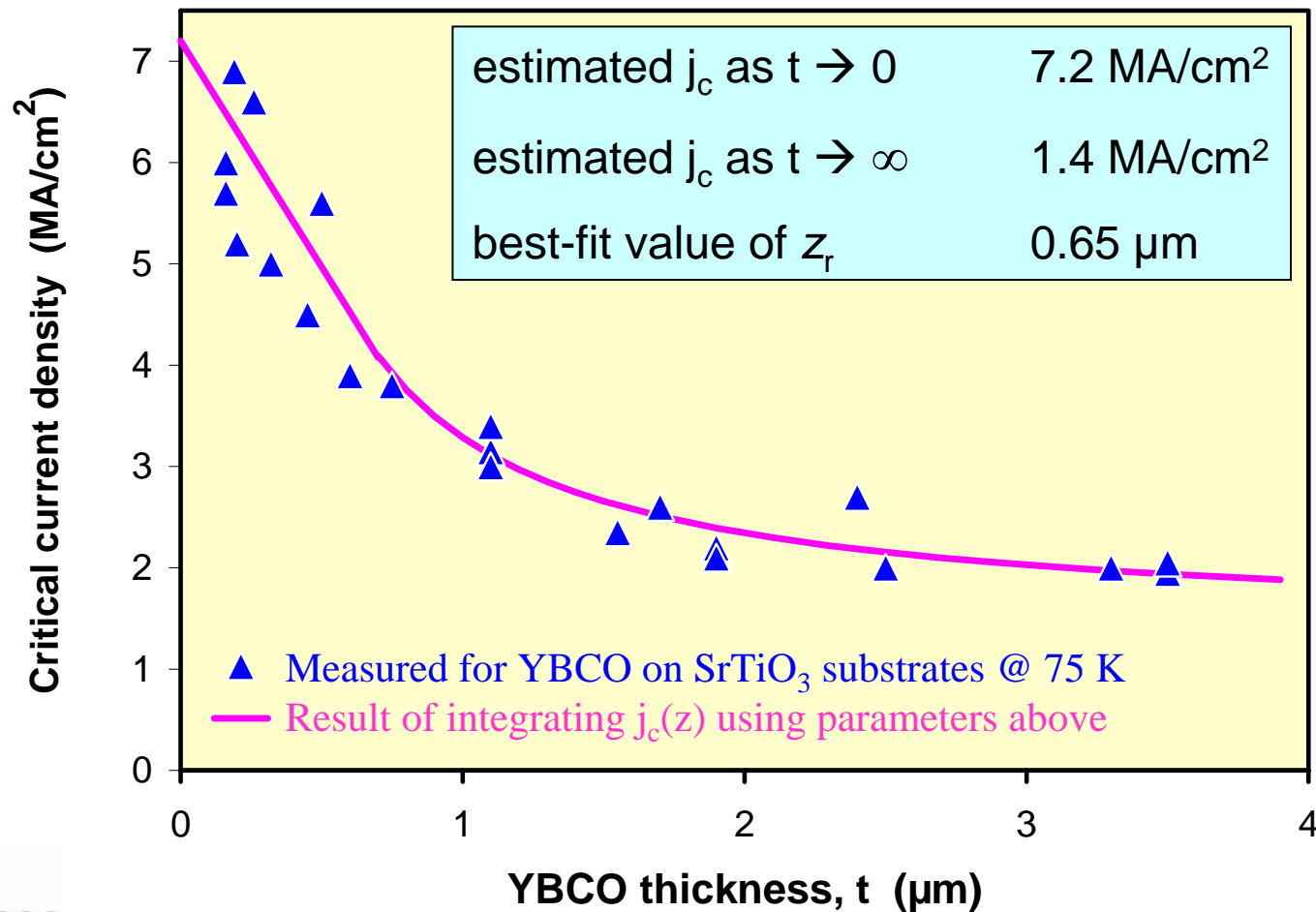
Expected  $J_c$  for 0.55 μm single layer is 4.75 MA/cm<sup>2</sup>.

Measured  $J_c$  for 3.5 μm multilayer (six 0.55 μm YBCO layers) is 4.0 MA/cm<sup>2</sup>.

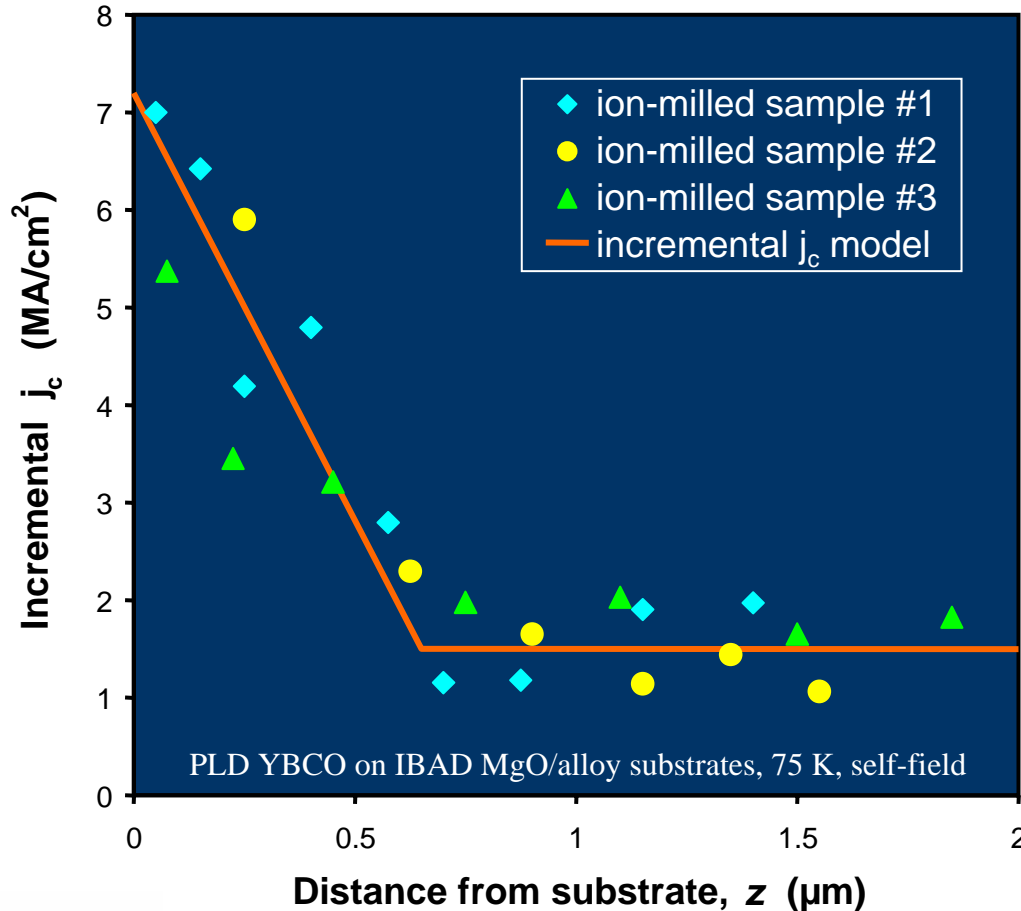
# To investigate how multilayers work we developed a model for the incremental $j_c$ within a film ...



... that exactly reproduces measured  $J_c$  thickness dependence with one adjustable parameter

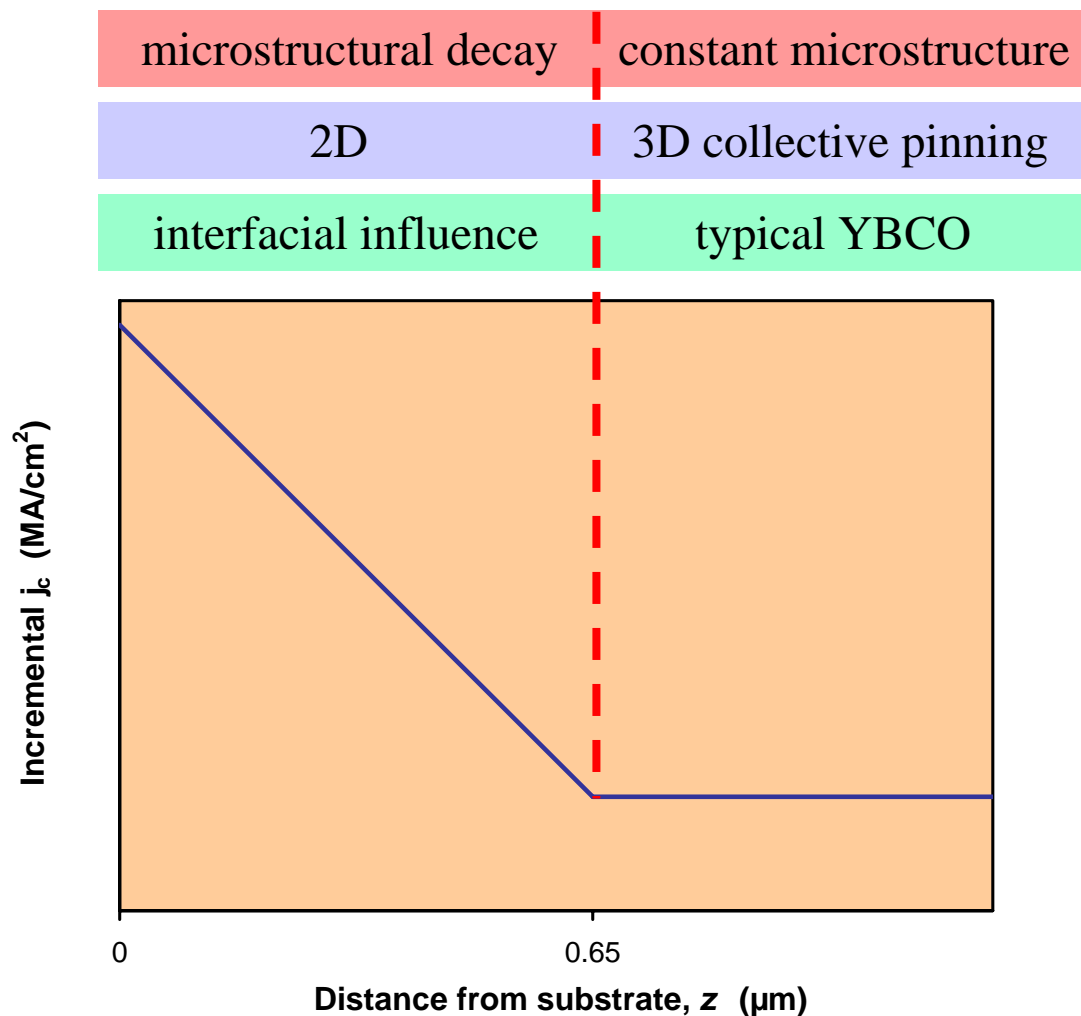


## And this year we validated the model by comparing it with $j_c(z)$ obtained from ion-milling data



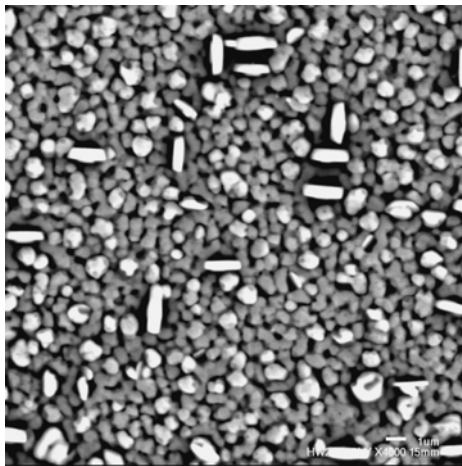
- Measure sample  $I_c$
- Remove thin layer by ion milling
- Measure  $I_c$  of remainder
- Calculate  $\Delta I_c$
- Measure layer thickness
- Calculate  $J_c$  of layer
- Repeat until  $t = 0$

# The next step was to investigate three possible explanations for the shape of the incremental $j_c$ function

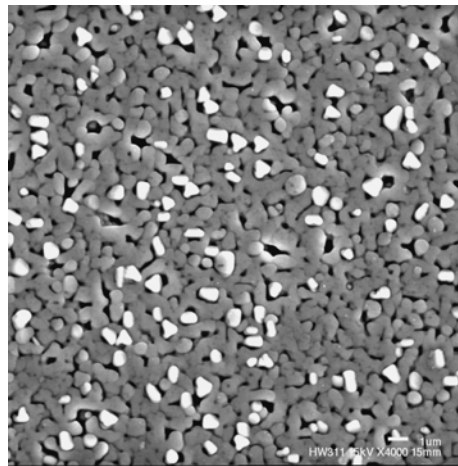


# The first hypothesis we tested is that microstructural decay is responsible for decrease of $J_c$ with thickness

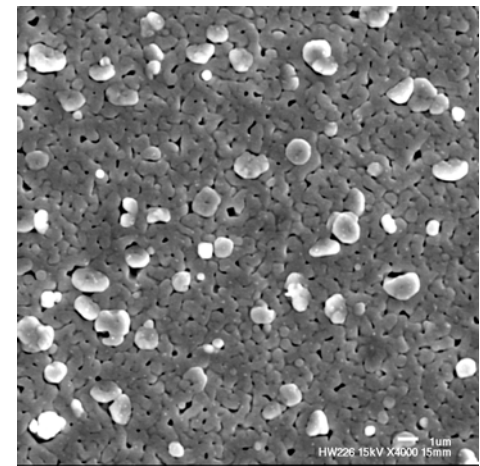
SEM images show that multilayers using either SmBCO or  $\text{CeO}_2$  interlayers improve morphology (substrates: IBAD MgO on metal)



3.7  $\mu\text{m}$   
YBCO  
single-layer



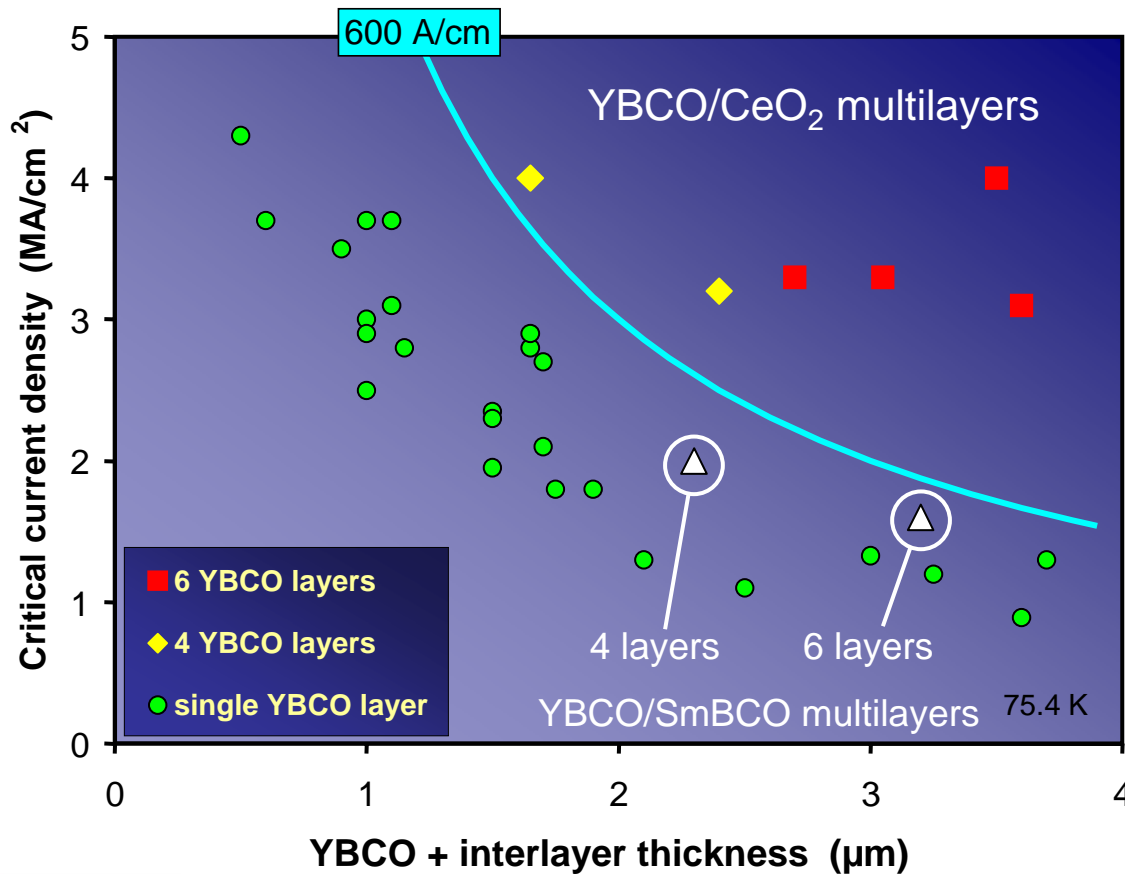
3.2  $\mu\text{m}$   
YBCO/SmBCO  
6-layer multilayer



3.1  $\mu\text{m}$   
YBCO/ $\text{CeO}_2$   
6-layer multilayer

image size: 25  $\mu\text{m}$  x 25  $\mu\text{m}$

# The difference between $\text{CeO}_2$ and SmBCO suggests that morphological improvement does not strongly affect $J_c(t)$



## Test

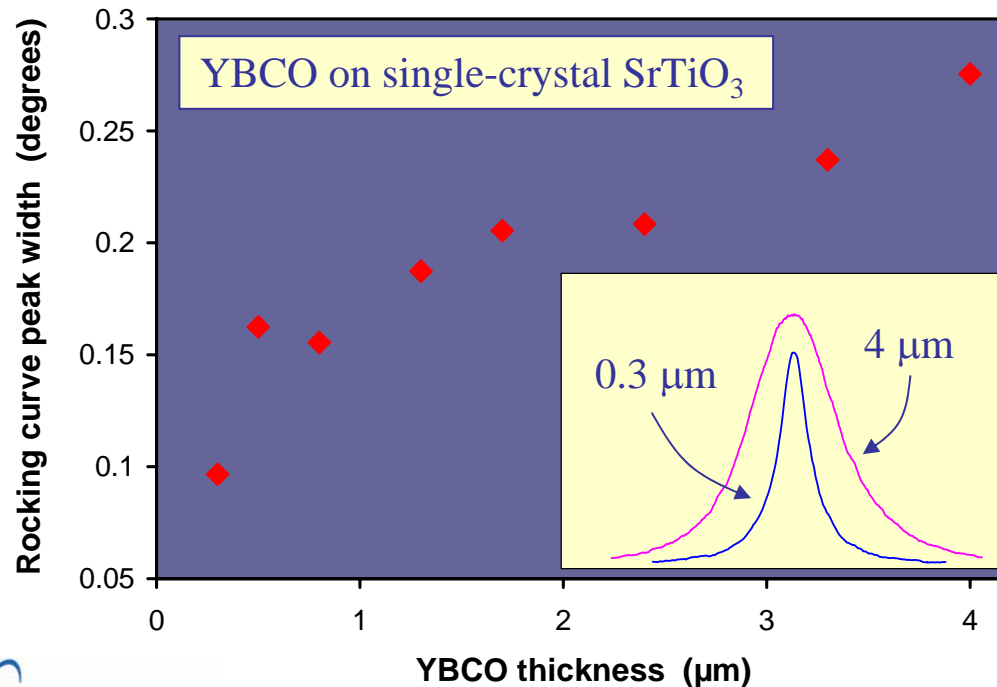
Replace  $\text{CeO}_2$  interlayers with SmBCO, keeping all other process conditions the same.

## Result

YBCO/SmBCO multilayers have  $J_c$  values more like YBCO single-layers

# Results showing definitive correlation between microstructure and $J_c$ are thus far elusive

- ➔ Microstructure does deteriorate with increasing film thickness...
- ➔ ...but it tends to do so linearly, unlike  $J_c$
- ➔ If linear trend continues, microstructural decay will eventually dominate  $J_c$



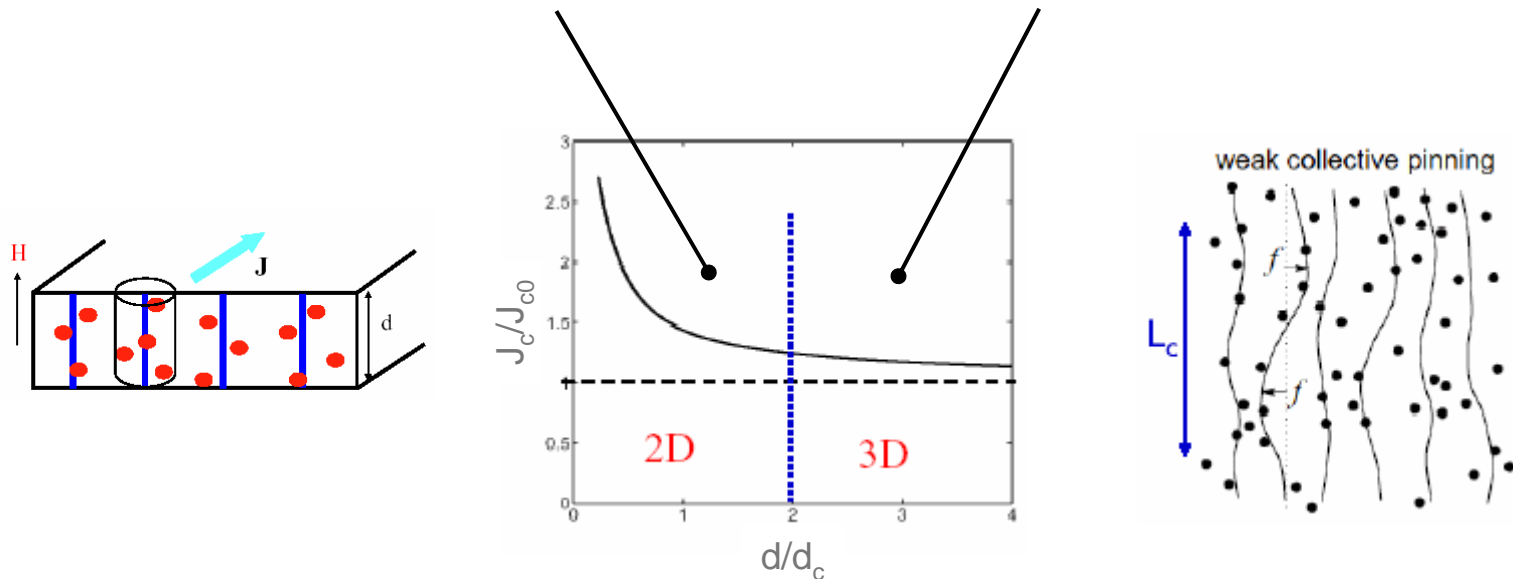
Similar results for variation of:

- \* 45-degree-rotated YBCO grains
- \* RBS channeling
- \* film density
- \* average screw dislocation density

# A second potential explanation for $J_c(t)$ is a 2D-to-3D crossover in the collective pinning regime

Short vortices in thinner films are rigid and cannot easily accommodate to random pinning sites.  $J_c$  is proportional to (thickness) $^{-1/2}$

Longer vortices in thicker films can more easily flex to intersect random pinning sites.  $J_c$  is constant.



A. Gurevich, *et al.*, presented at the Superconductivity for Electric Power Systems Annual Review, July 27-29, 2004, Washington DC

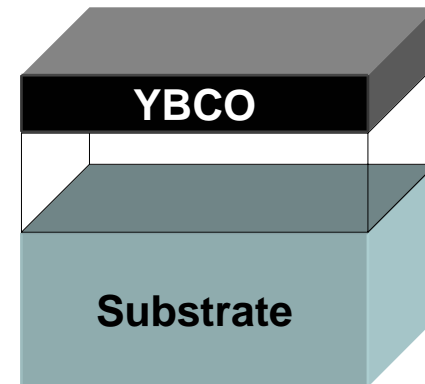
# To test this hypothesis we need a way to isolate and measure slabs of YBCO from a thick film...

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...because in the 2D-3D model,  $J_c$  is determined by the YBCO thickness and will be constant regardless of the slab's location in the film

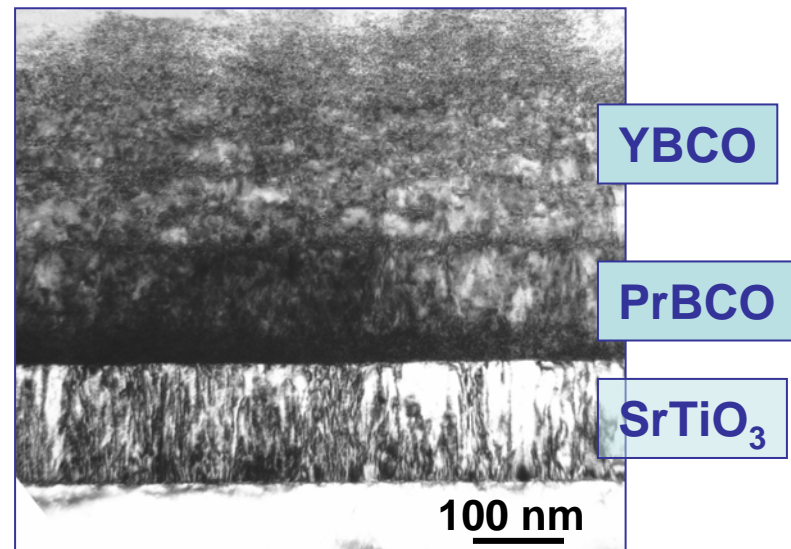
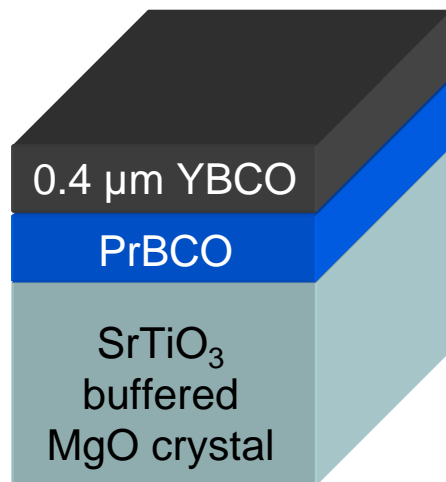
Since we cannot remove a slab and measure it, we need to deposit films on “invisible” spacer layers having the following properties:

- ➔ not superconducting
- ➔ a perfect lattice match to YBCO

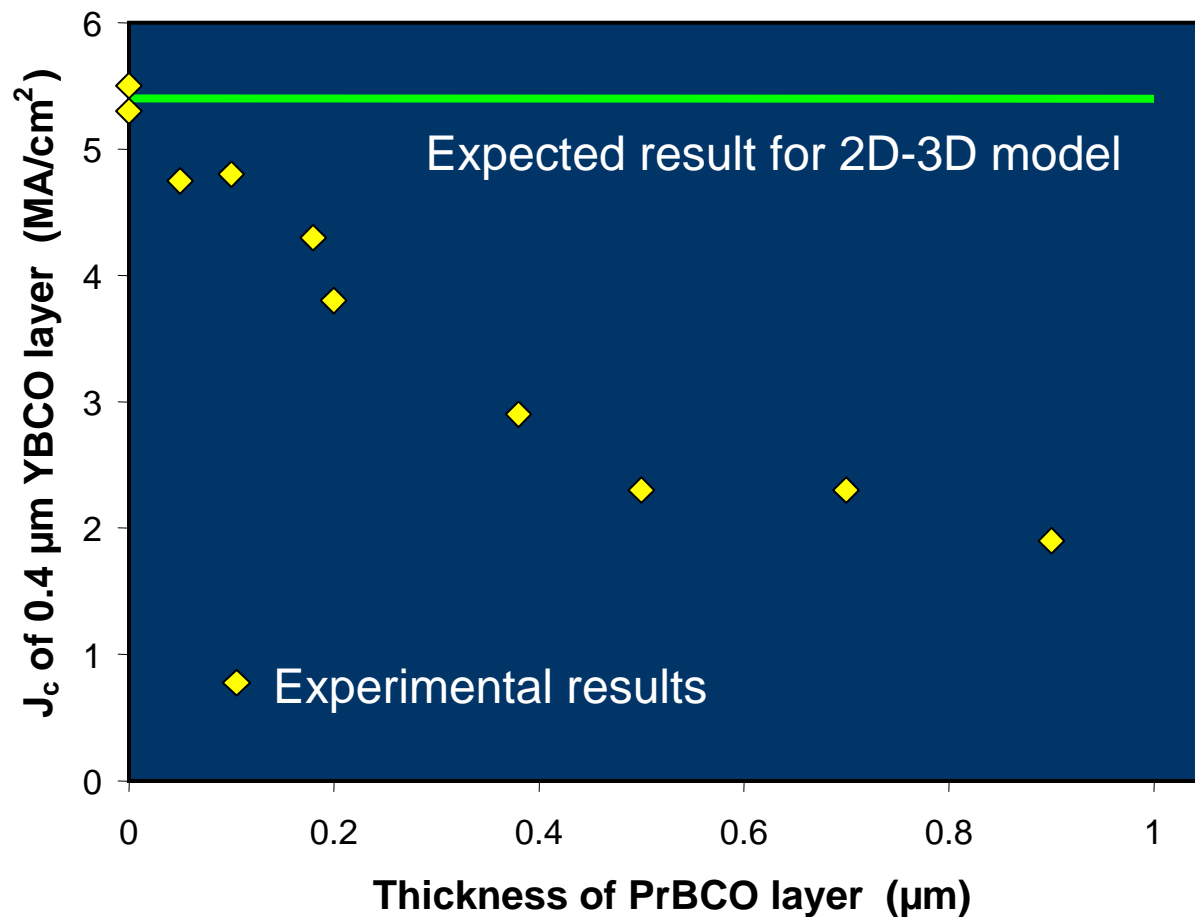


# PrBCO closely matches the invisibility criteria, so we made a series of bilayers with varying PrBCO thickness

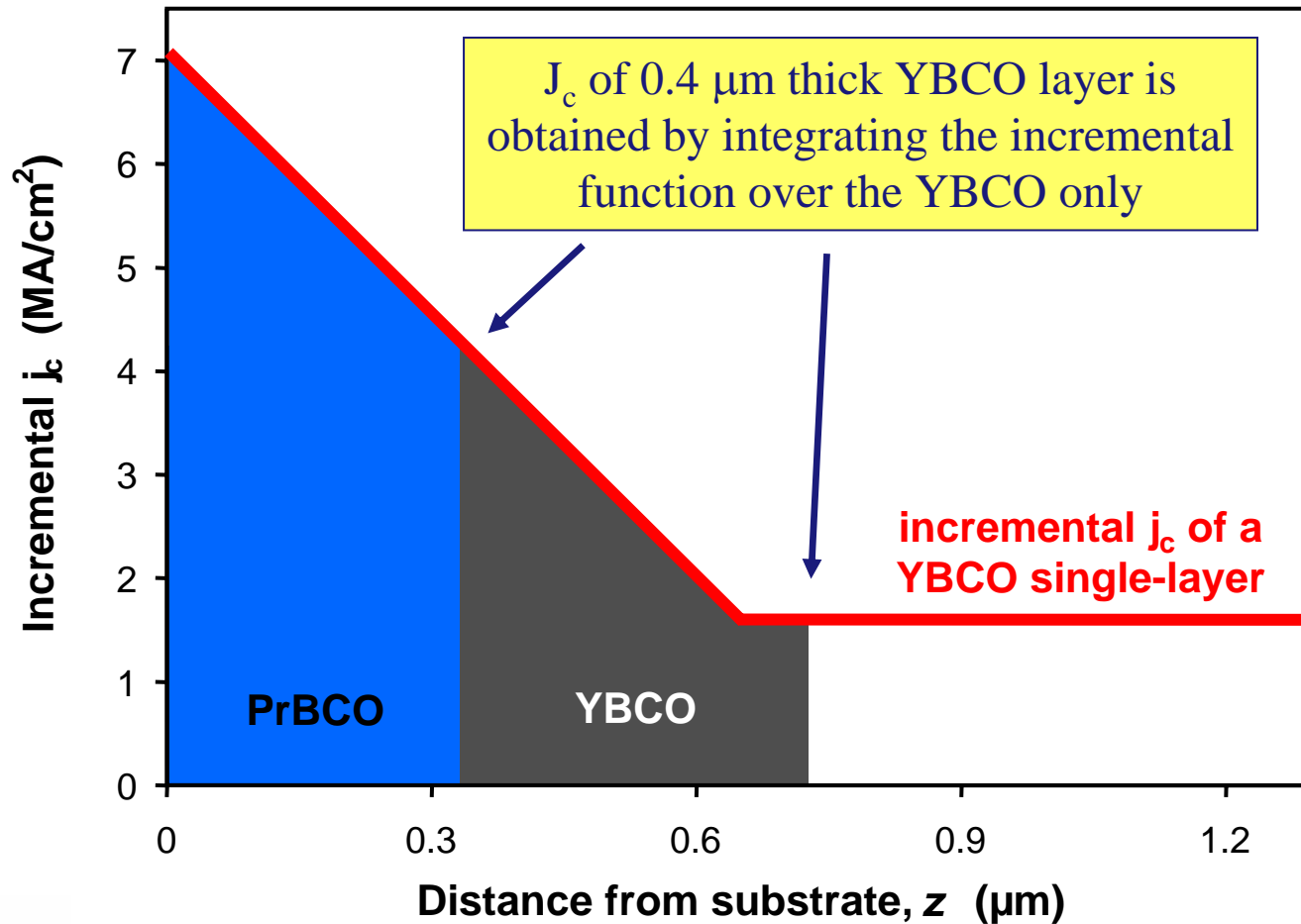
- ➔ Nonsuperconducting PrBCO isolates vortices from the defect-rich interface.
- ➔ The PrBCO/YBCO interface is nearly homoepitaxial and relatively free of defects.



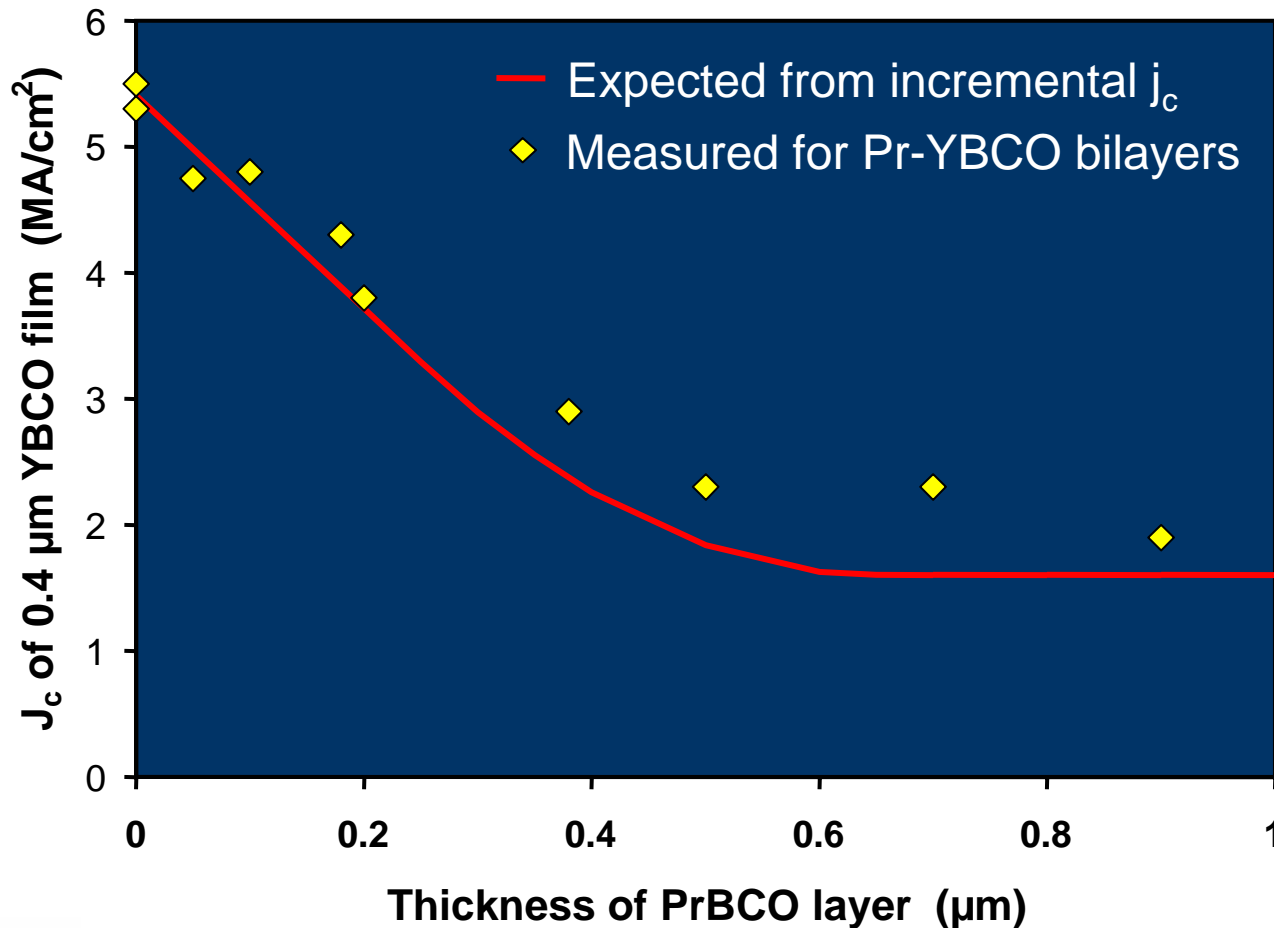
## Result: Constant $J_c$ s predicted by the 2D-3D crossover model are not observed in the PrBCO/YBCO bilayers



But if we calculate  $J_c$  of the bilayer films based on the incremental  $j_c$  function ...

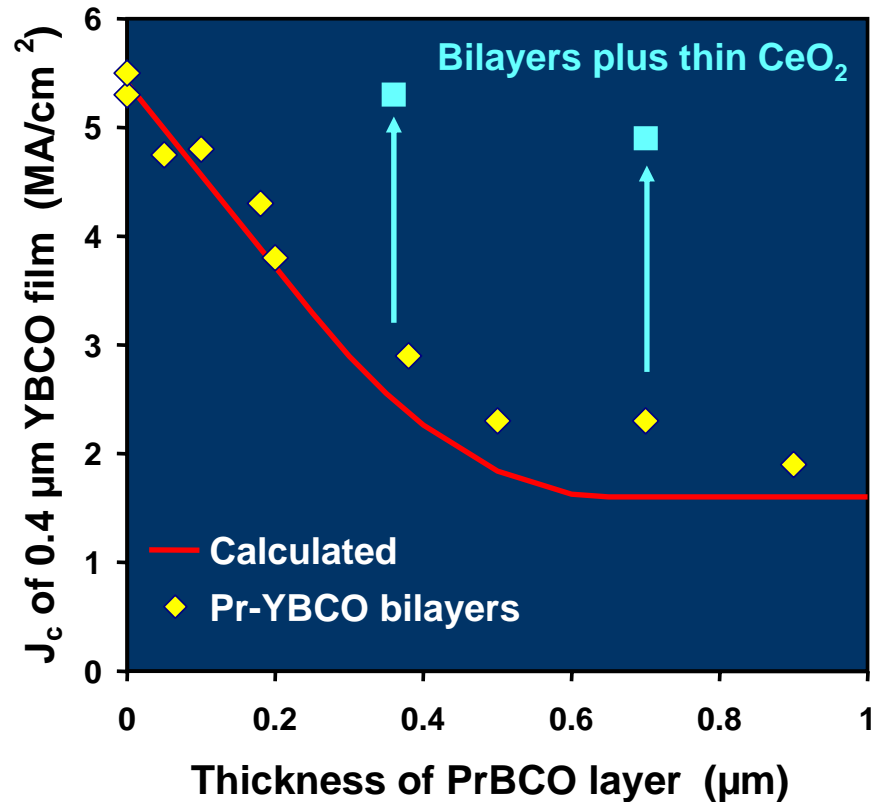
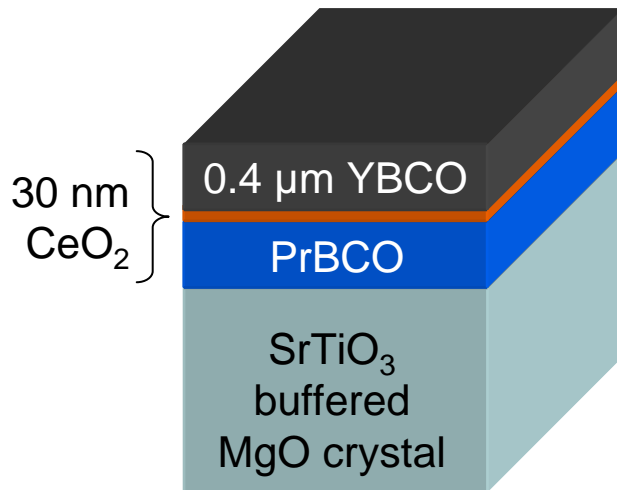


...experimental results match the calculation,  
suggesting that  $J_c(t)$  is interface-related

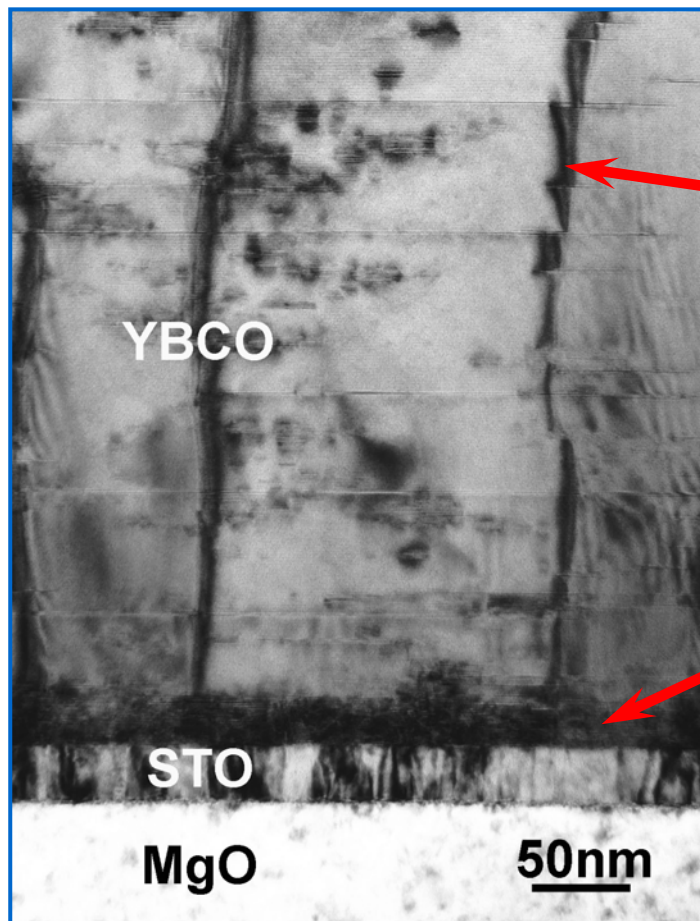


# Importance of the interface is further supported by adding a $\text{CeO}_2$ layer between PrBCO and YBCO

The  $\text{CeO}_2$  layer restores  $J_c$  to the level of a 0.4  $\mu\text{m}$  YBCO single layer film



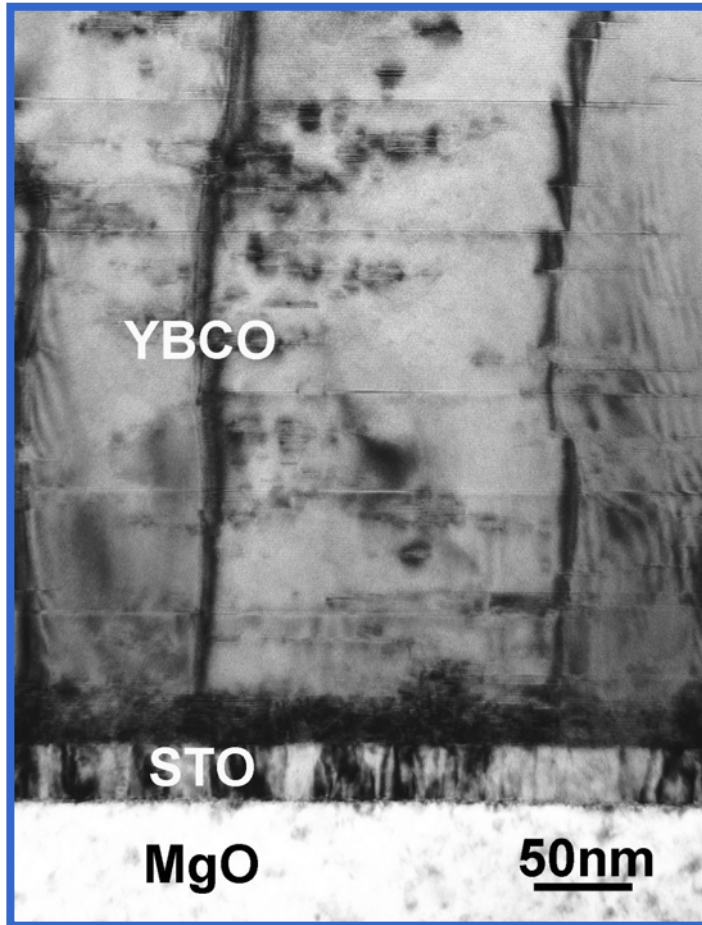
# What is the source of strong pinning near the interface?



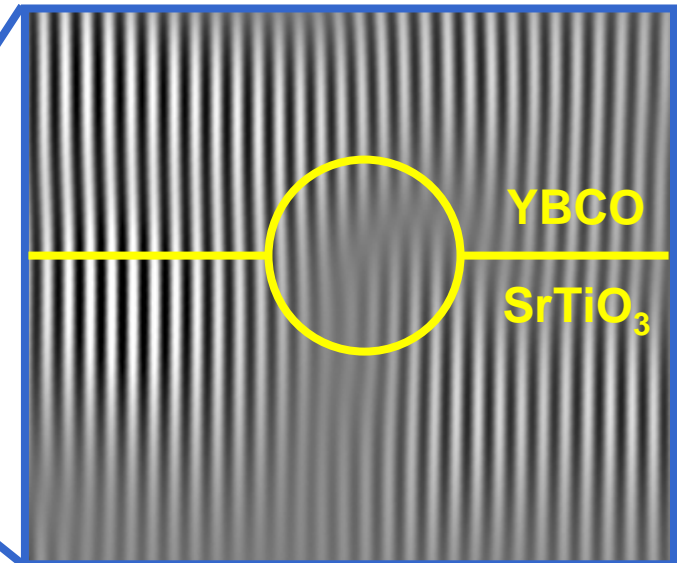
Threading dislocations between growth columns are the kind of defect that can give rise to the constant  $j_c$  observed beyond  $0.65 \mu\text{m}$ .

A dark band near the YBCO-buffer interface indicates a higher density of defects that could produce strong pinning at the film-substrate interface.

# The dark band is due to misfit dislocations at the YBCO-buffer interface

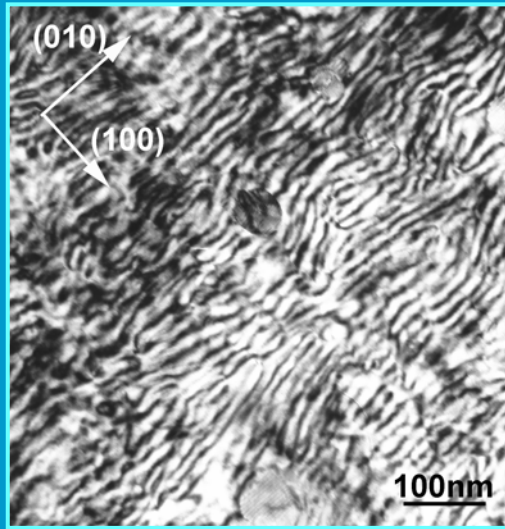
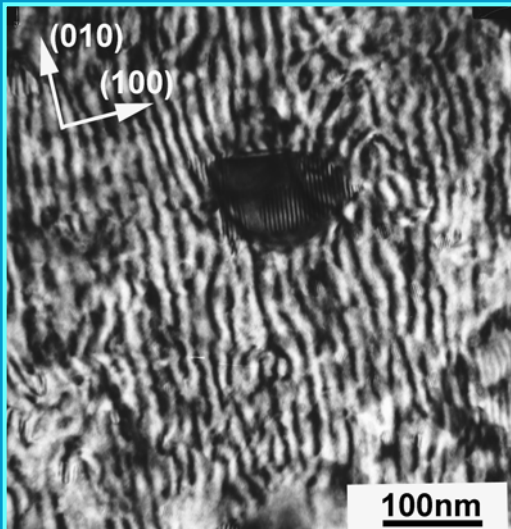


Fast Fourier Filtered Image of a high-resolution cross section shows that the dark band is due to misfit dislocations at the interface.



# The dislocations are parallel to the YBCO b-axis because of larger misfit with the a-axis

TEM plan views of a ~ 20 nm thick YBCO film on a  $\text{SrTiO}_3$  single-crystal substrate  
Misfit dislocations have also been observed at the YBCO- $\text{CeO}_2$  interface



Misfit between  
 $\text{SrTiO}_3$  lattice and:

YBCO a-axis – 2.4 %

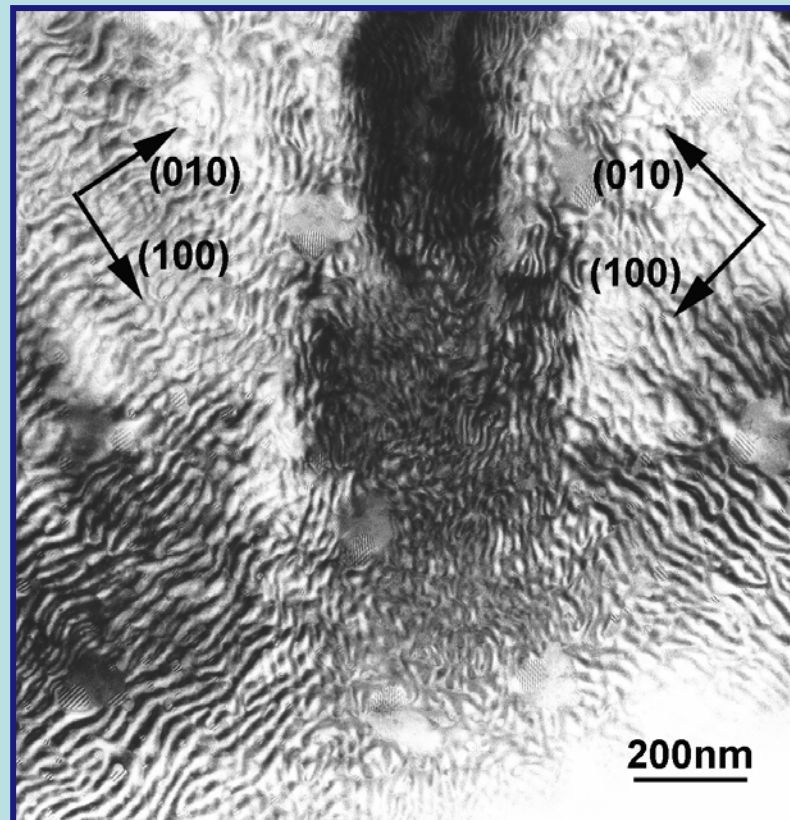
YBCO b-axis – 0.7 %

Spacing of ~ 17 nm is  
consistent with a-axis  
misfit

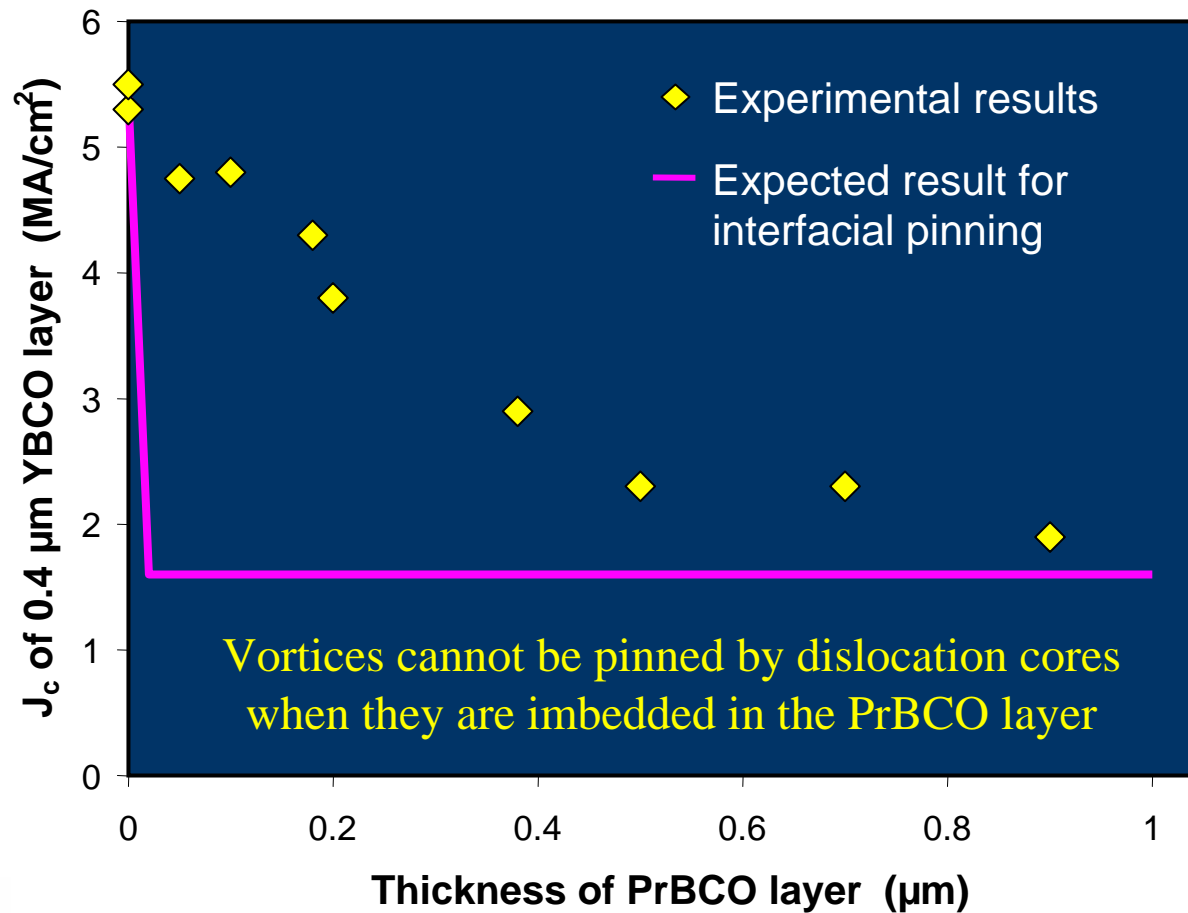
Since the a-axis has two possible orientations, misfit dislocations form a net that seems ideal for strong pinning

TEM plan view showing two adjacent growth islands in a 20 nm thick YBCO film on  $\text{SrTiO}_3$ .

The YBCO a- and b-axes for the two islands are rotated 90 degrees with respect to one another and the misfit dislocations in each island are orthogonal.



# But strong pinning by the dislocation cores is inconsistent with the PrBCO bilayer experiment...



...because enhanced  $j_c$  extends  $0.65\text{ }\mu\text{m}$  into the film – far beyond the thickness of the heavily defected layer

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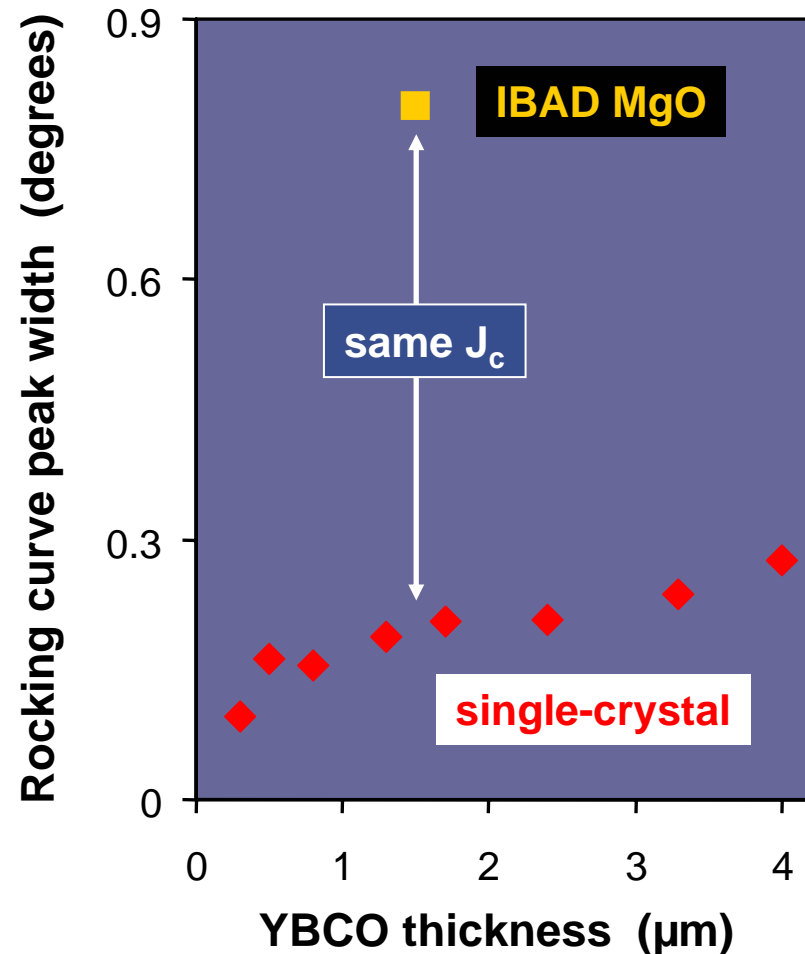
*And this value has remained constant throughout the history of our work on the thickness dependence of  $J_c$*

SUBSTRATE TYPE	Single-crystal YSZ + CeO <sub>2</sub>	IBAD YSZ + CeO <sub>2</sub>	Single-crystal SrTiO <sub>3</sub> and IBAD MgO + SrTiO <sub>3</sub>	Single-crystal MgO + SrTiO <sub>3</sub>
YEAR	1993	1999	2004	2005
$j_c$ at interface	5.5 MA/cm <sup>2</sup>	3.8	7.2	7.1
bulk $j_c$	0.75 MA/cm <sup>2</sup>	0.5	1.4	1.6
range* – $z_r$	0.65 $\mu\text{m}$	0.65	0.65	0.65

# Evidence is not yet sufficient to determine whether microstructural decay causes $J_c$ thickness dependence

→ SmBCO and  $\text{CeO}_2$  interlayers both improve film morphology and texture, but multilayers have very different  $J_c$ .

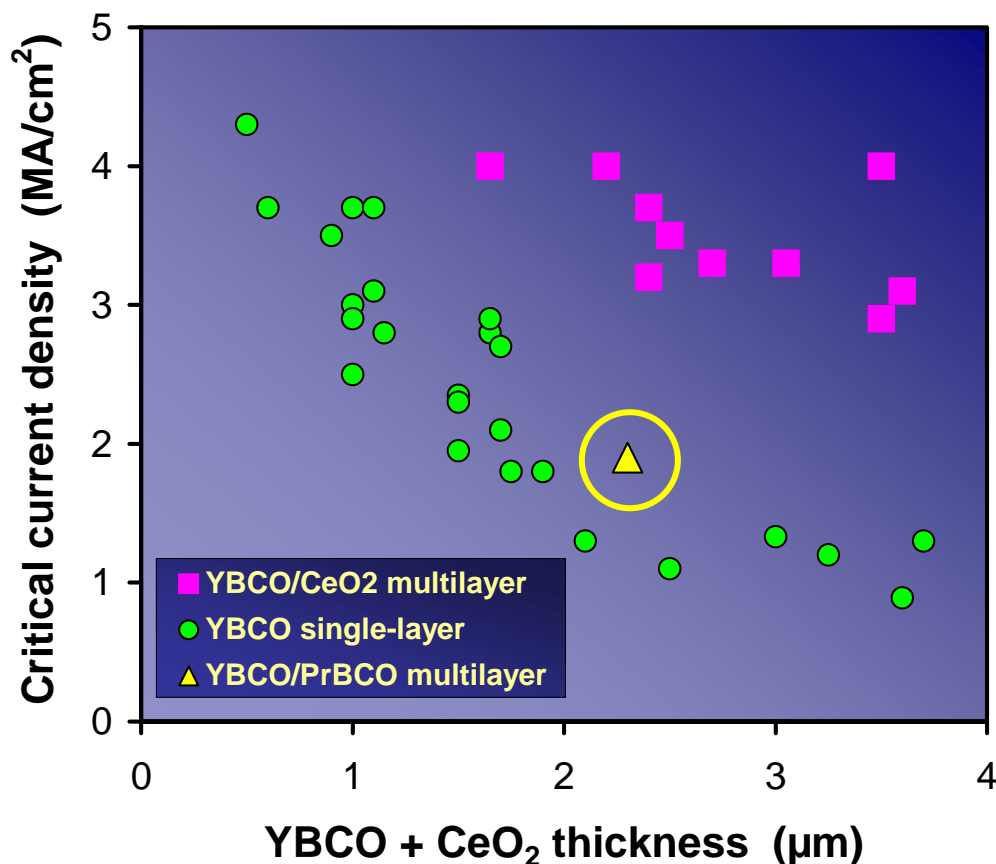
→ Apparent correlations between  $J_c$  and microstructure can be misleading. →



# Intrinsic effects such as a 2D-3D crossover are not responsible for $J_c$ thickness dependence

→ In bilayer experiments,  $J_c$  of 0.4  $\mu\text{m}$  YBCO layer should be independent of PrBCO thickness – it is not.

→ PrBCO-based multilayers should have  $J_c$  comparable to  $\text{CeO}_2$ , but they do not. →

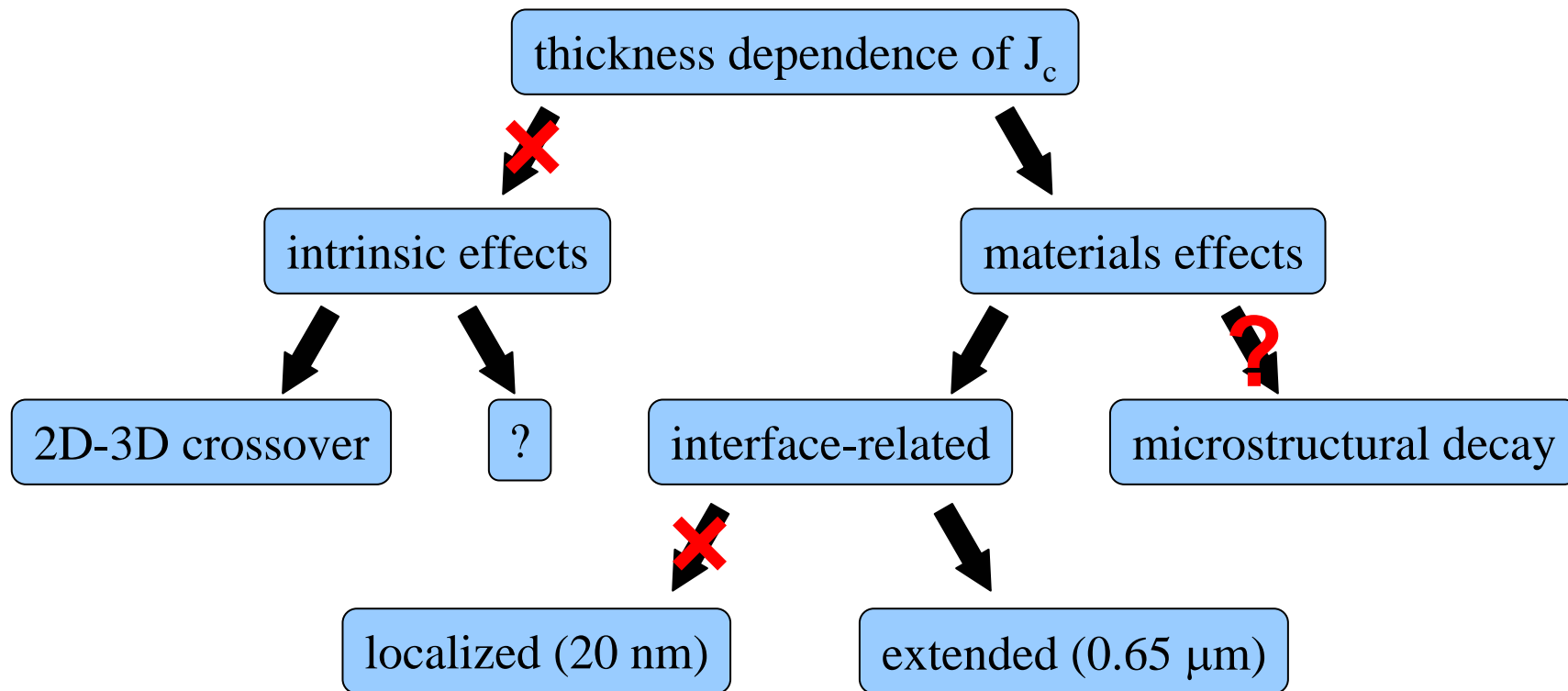


# There is much evidence that $J_c$ thickness dependence is due to enhanced pinning near the interface

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- The highest incremental  $j_c$  occurs nearest the interface
- Heteroepitaxial interfaces (e.g.  $\text{CeO}_2/\text{YBCO}$  or  $\text{Y}_2\text{O}_3/\text{YBCO}$ ), which contain misfit dislocations, result in high- $J_c$  multilayers.
- “Homoepitaxial” interfaces (e.g.  $\text{SmBCO}/\text{YBCO}$  or  $\text{PrBCO}/\text{YBCO}$ ), which contain relatively fewer defects, do not increase multilayer  $J_c$ .
- Moving YBCO farther from the interface (with PrBCO) decreases  $J_c$  in a systematic way.

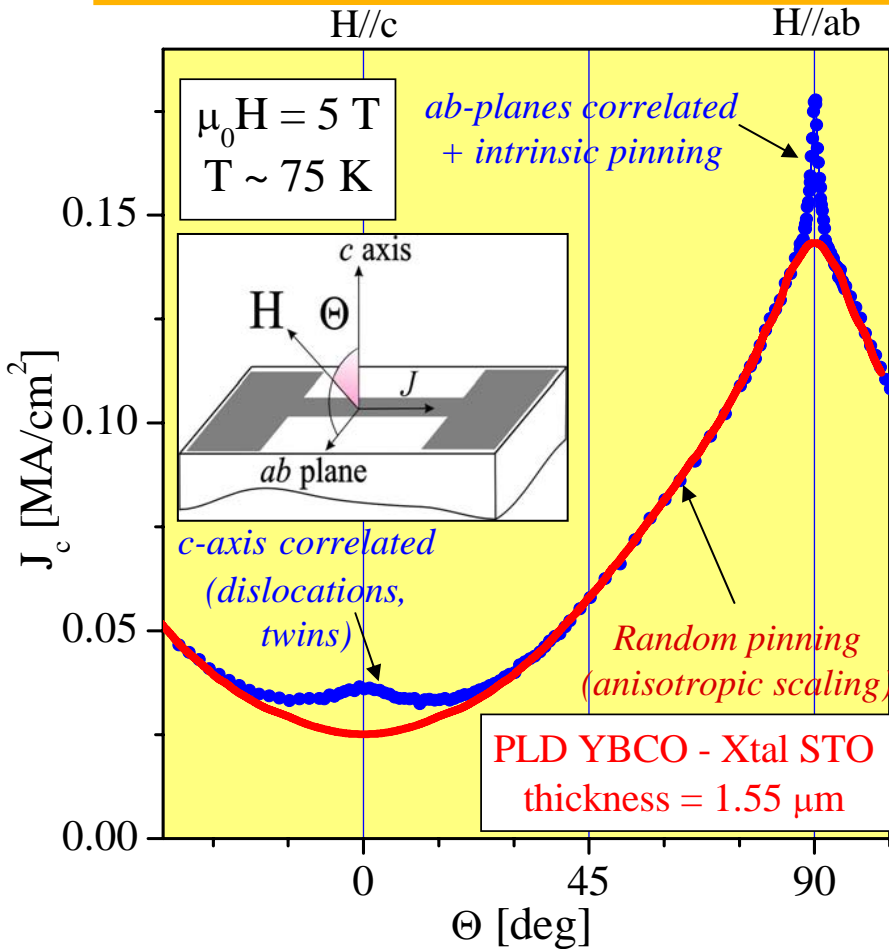
## So, in summary:



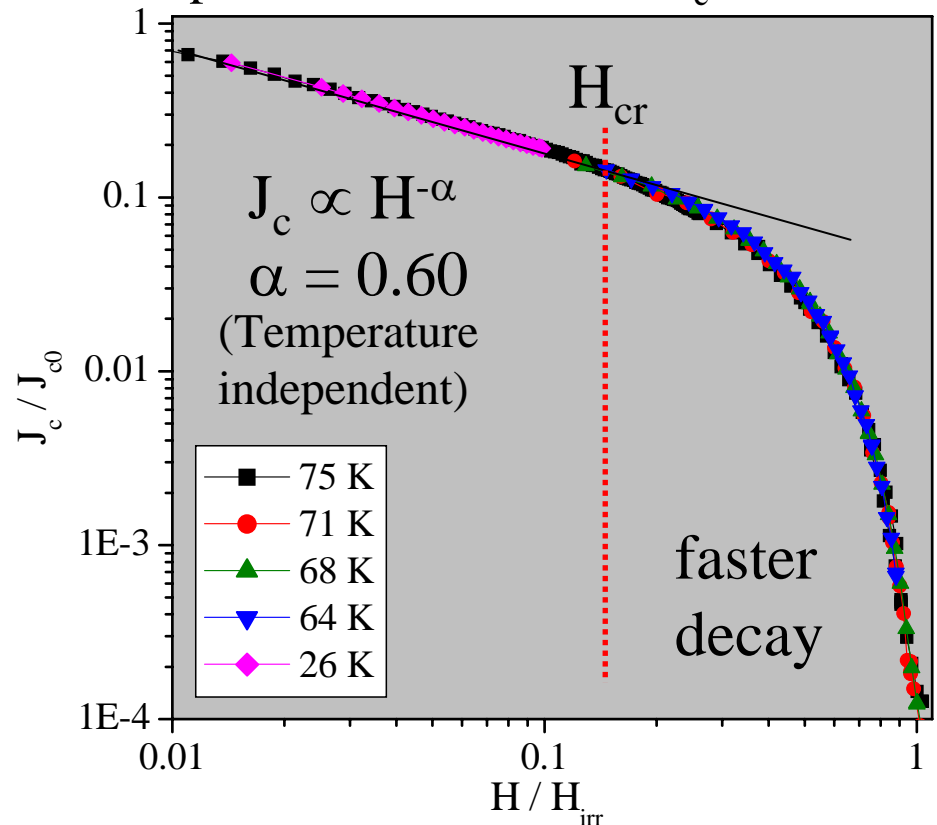
**What is the source of strong pinning near the interface?**

**We will obtain additional information from the in-field  $J_c$**

# We use the field, angular and temperature dependences of $J_c$ to identify pinning mechanisms and regimes

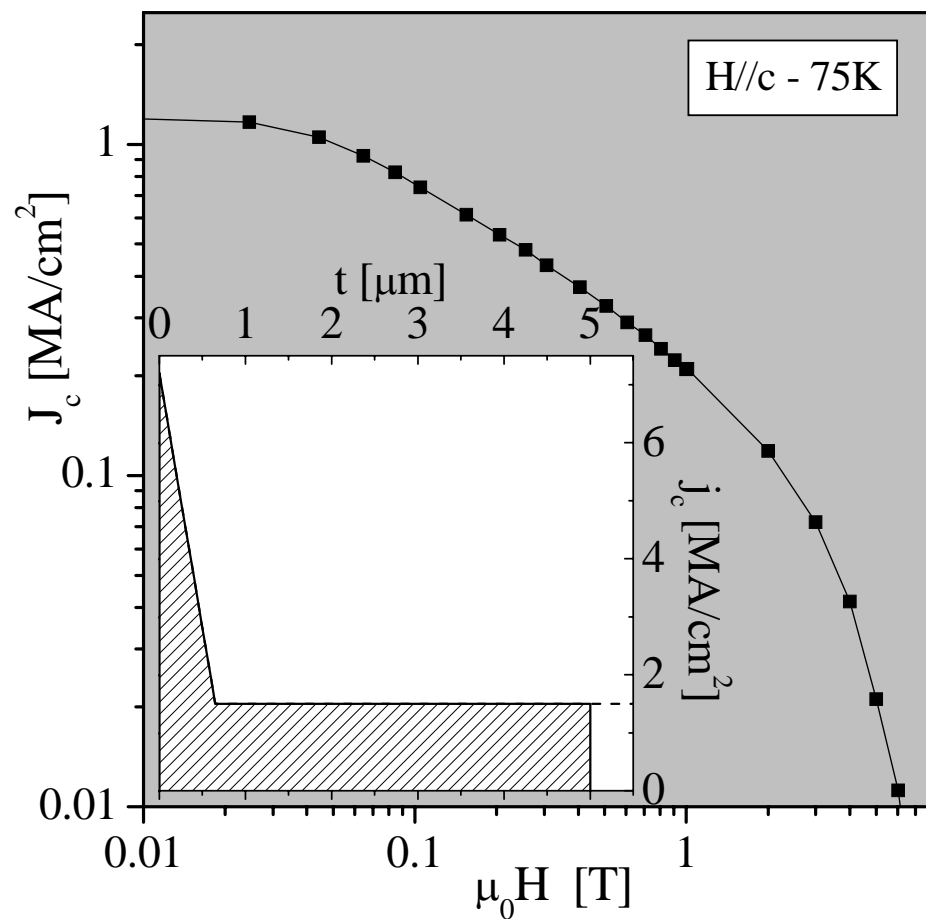
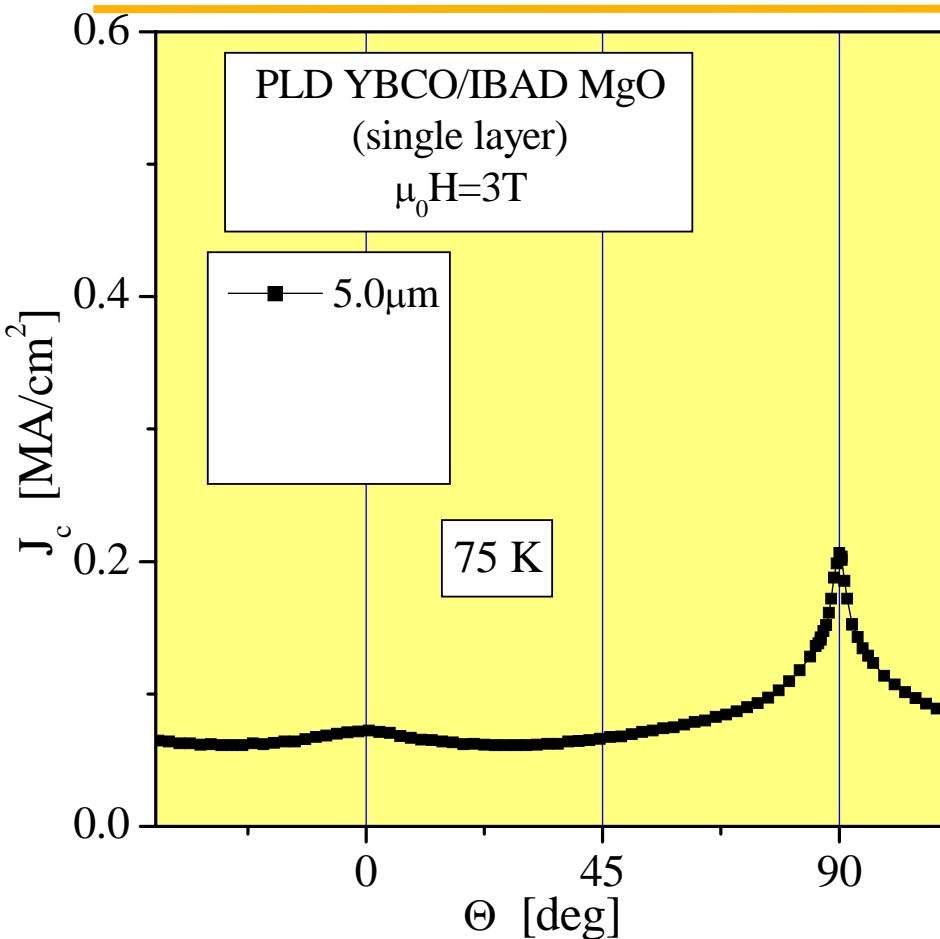


Of particular relevance is  $J_c$  for  $H//c$ :

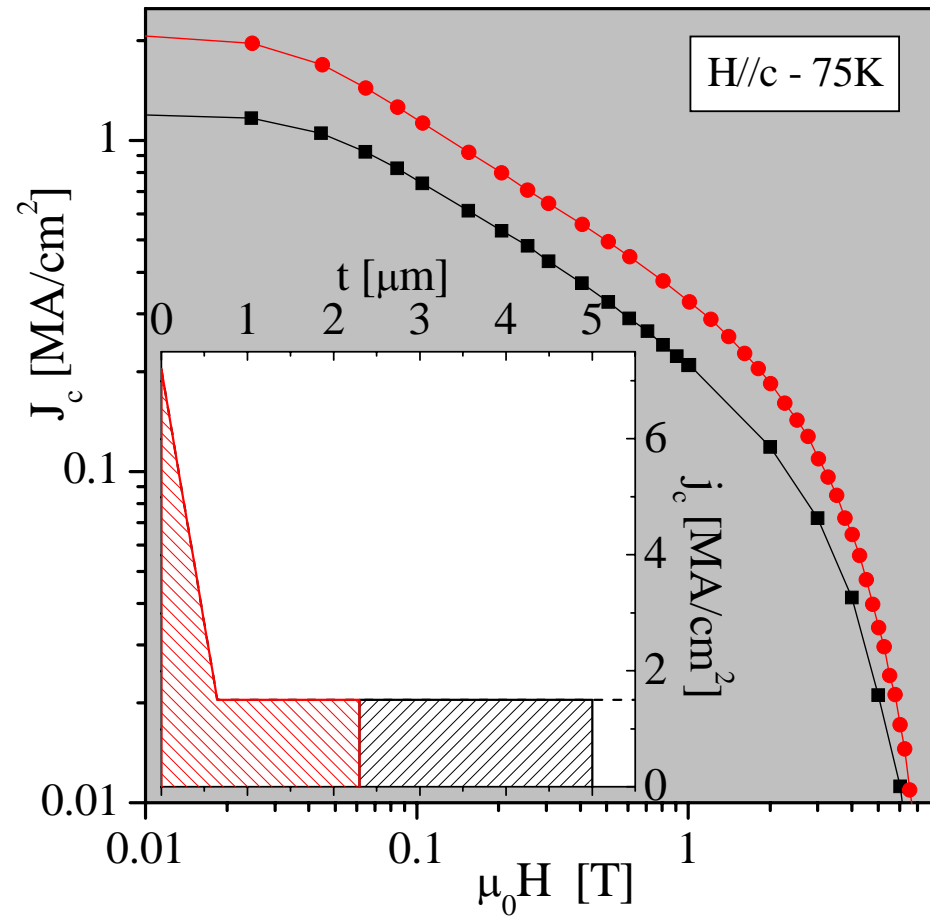
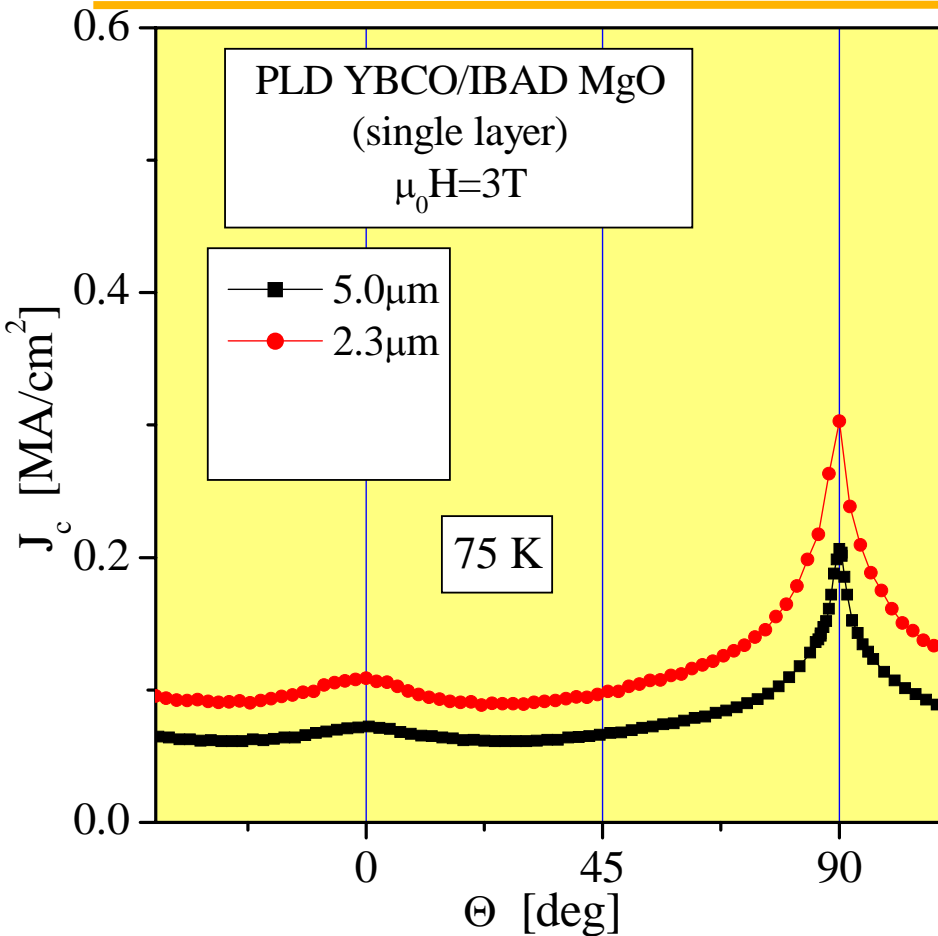


We will now apply these tools to investigate the thickness dependence

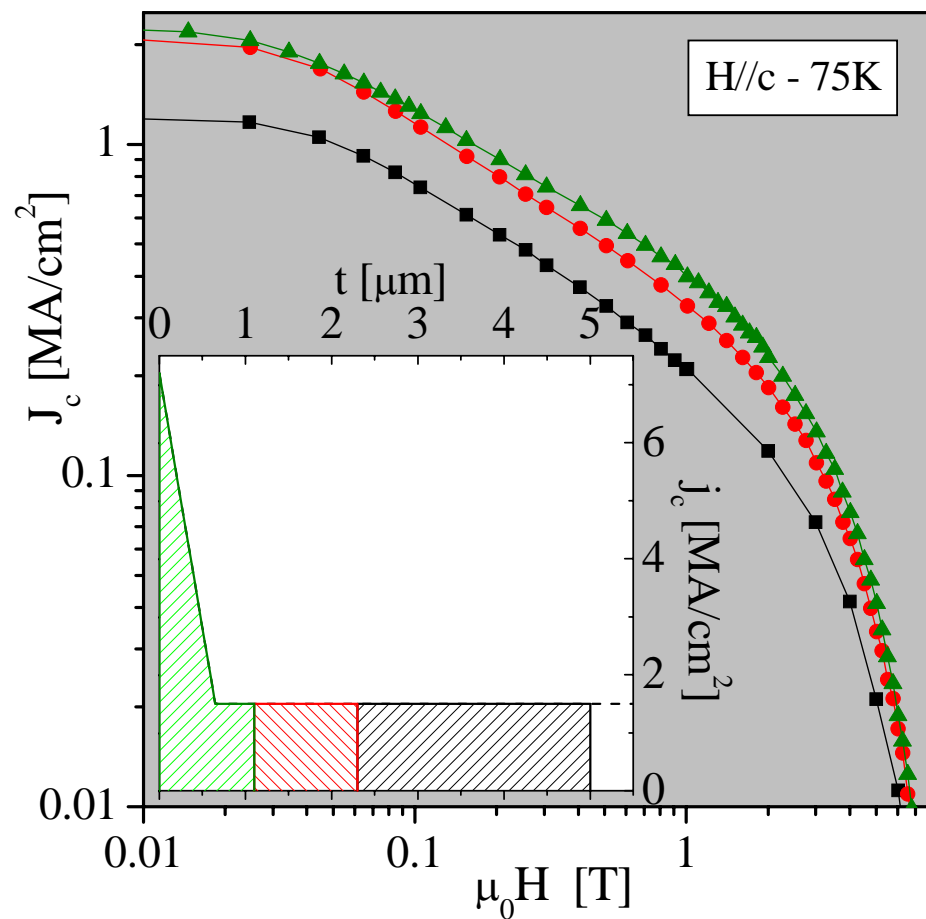
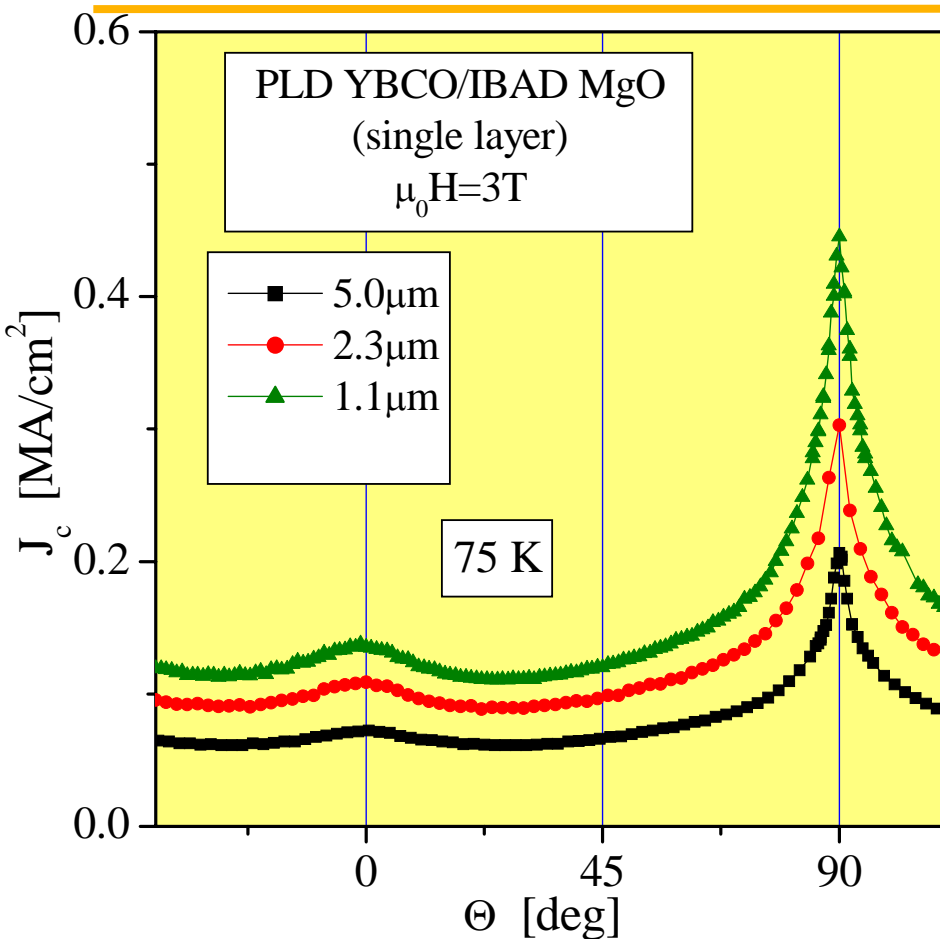
# Ion milling of a thick PLD film: from $t = 5\mu\text{m}$ to $t \sim 0.7\mu\text{m}$ the shape of $J_c(T, H, \Theta)$ remains almost the same



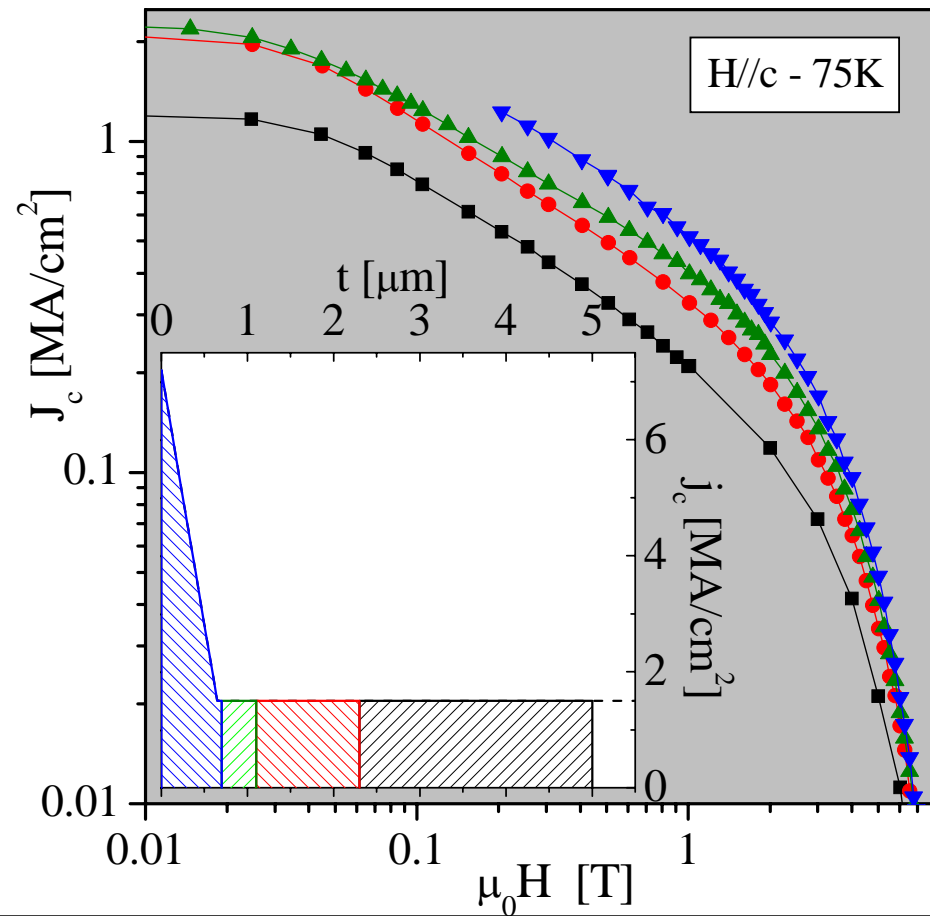
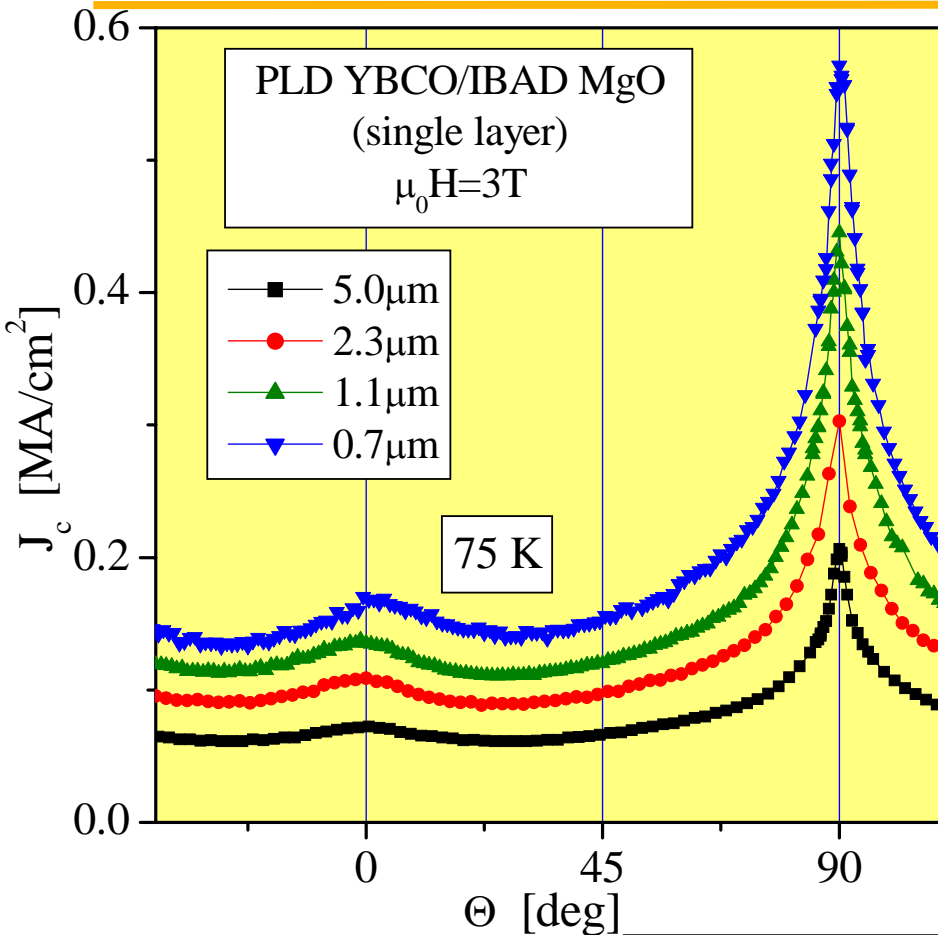
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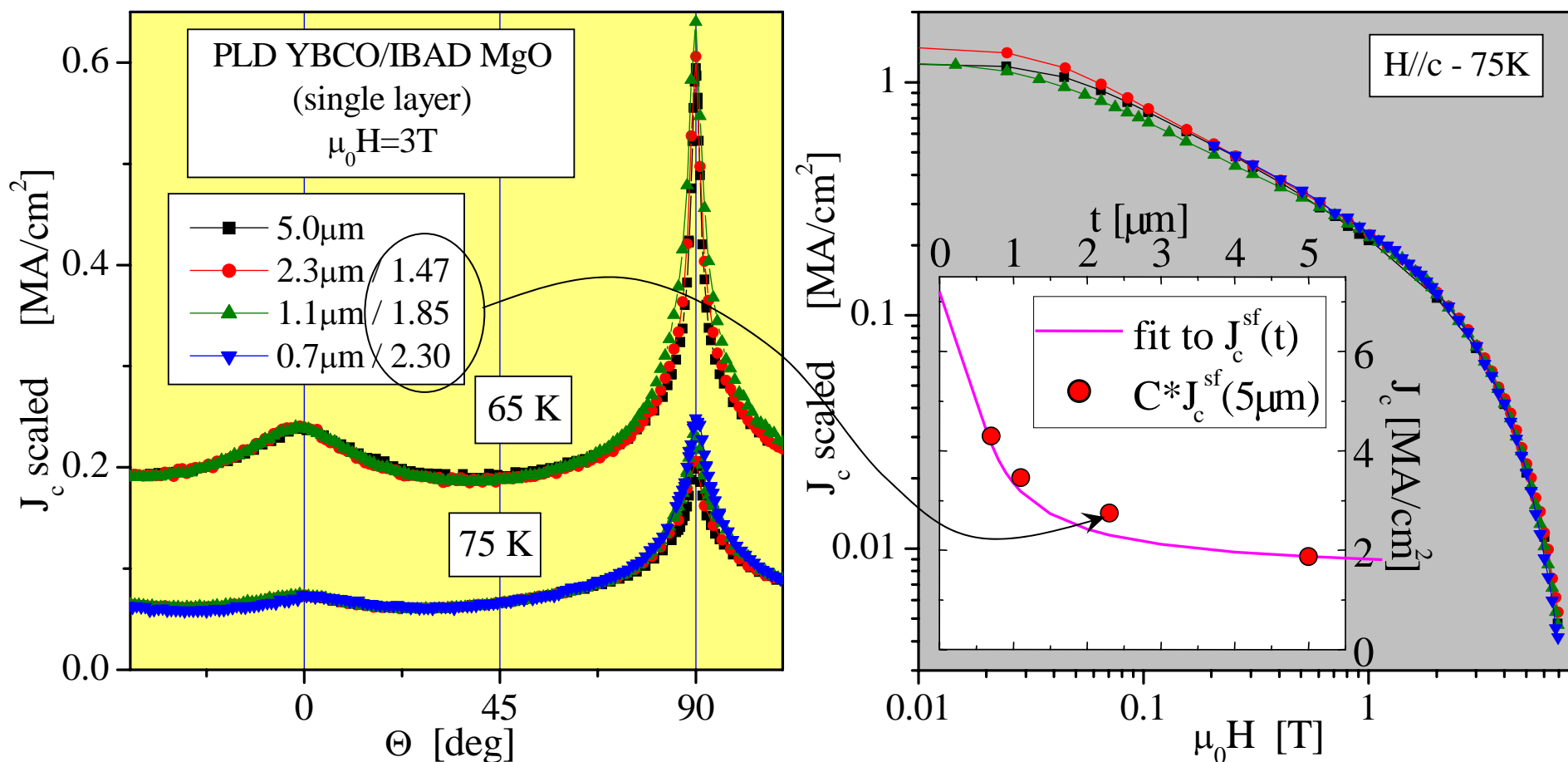


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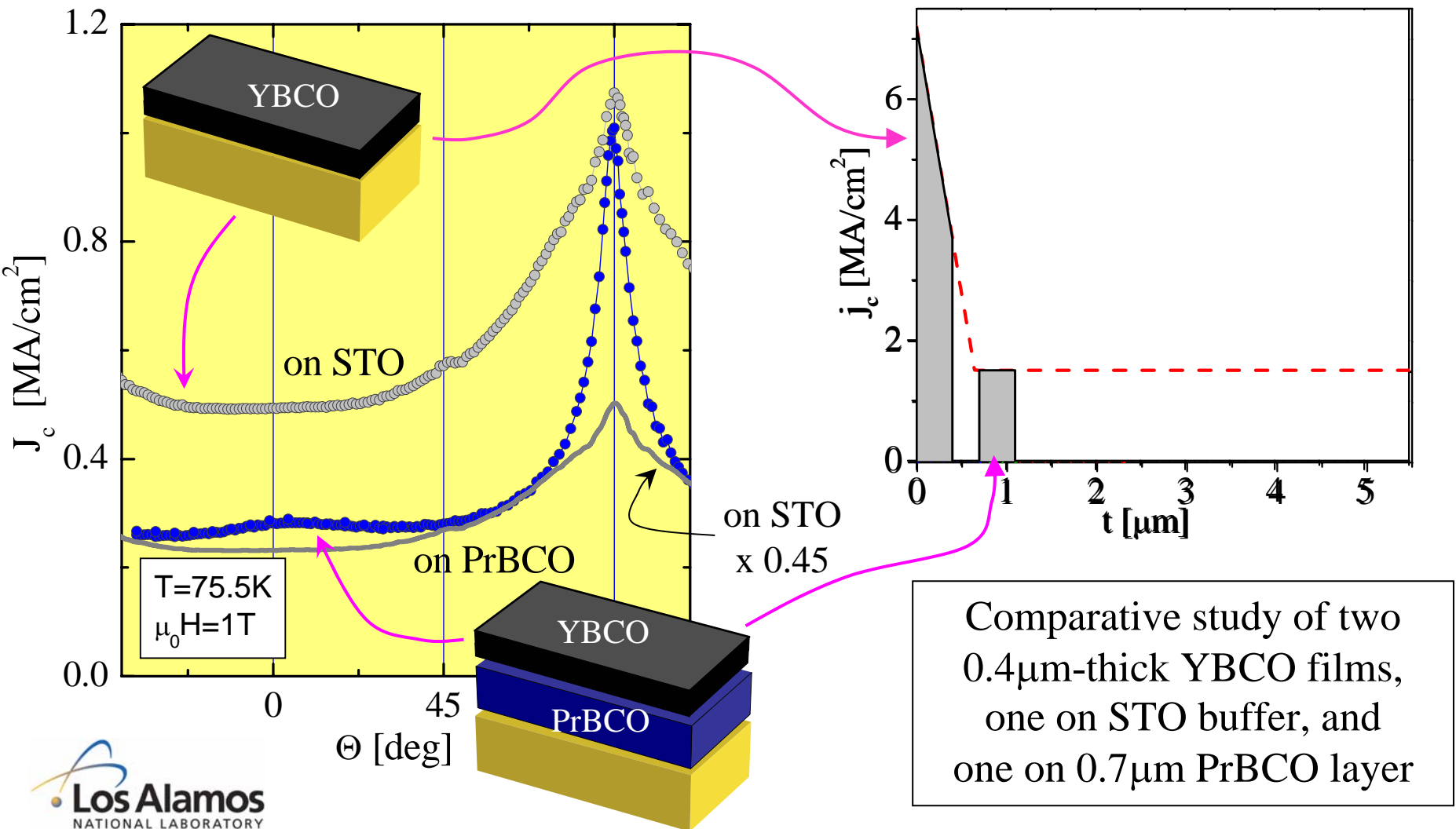
$J_c$  changes orders of magnitude, but *to first approximation*  
 $J_c(T, H, \Theta)_t \sim C * J_c(T, H, \Theta)_{5\mu\text{m}}$

Curves for all thicknesses can be overlapped by just dividing by a factor, which is the same one obtained for self field

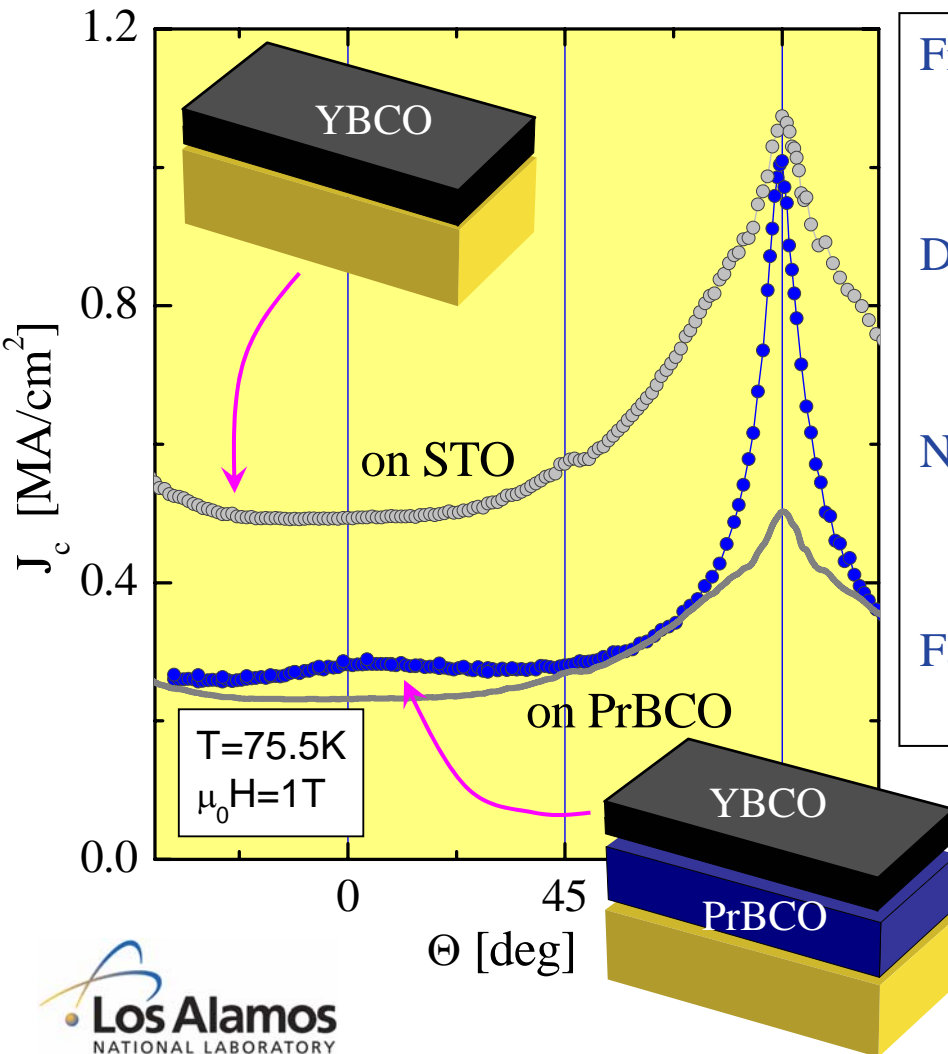


The thickness dependence is not related to vortex physics

# There are more and/or stronger defects near the interface. What else can we learn about them??



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Films of same thickness have different  $J_c$ :

- Film on STO has more and/or stronger pinning centers.

Different dependence on  $\Theta$ :

- Additional defects close to STO buffer are different from “bulk” defects.

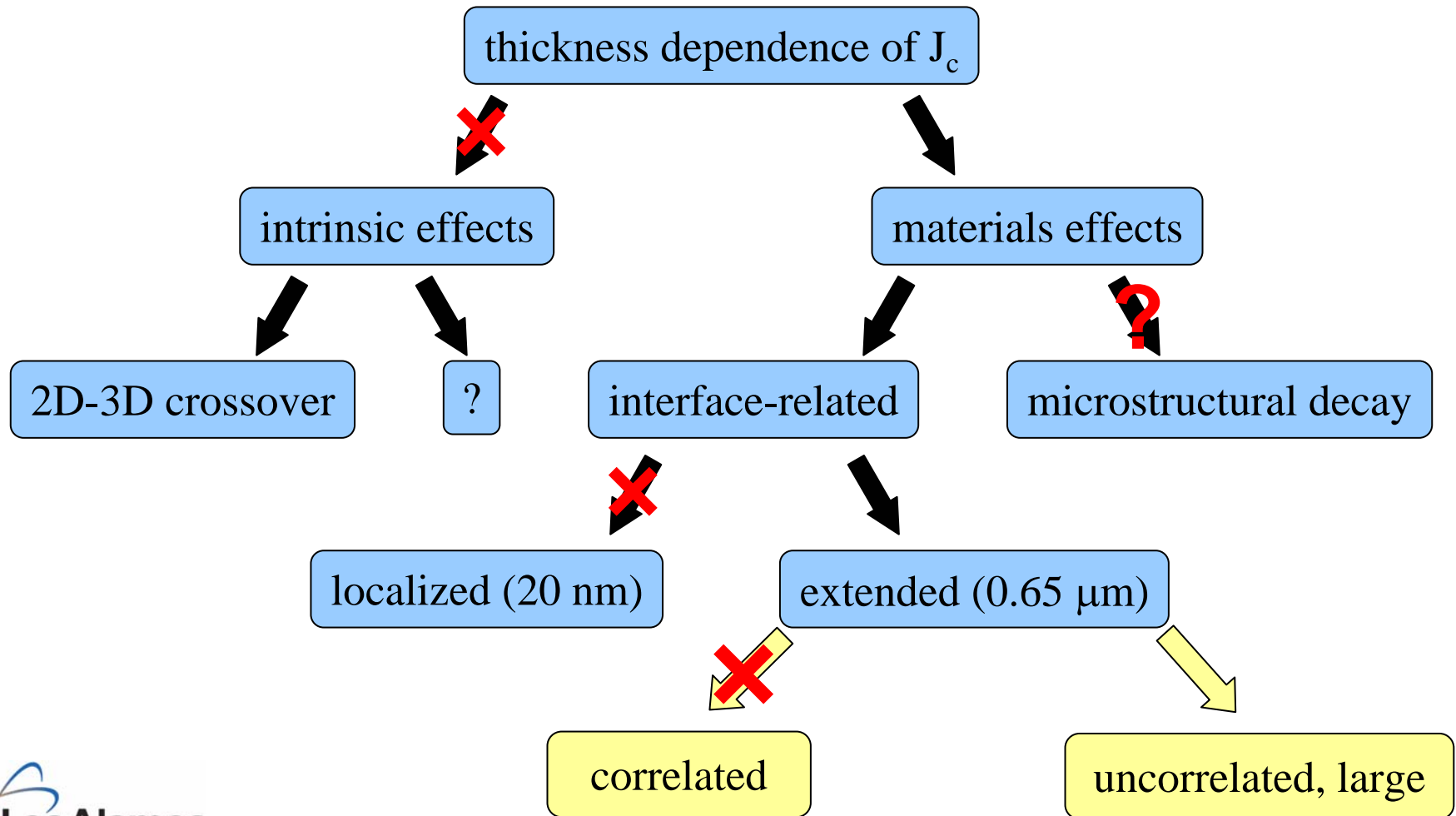
No large peaks for H//c & H//ab in film on STO:

- Suggests that the additional defects are uncorrelated.

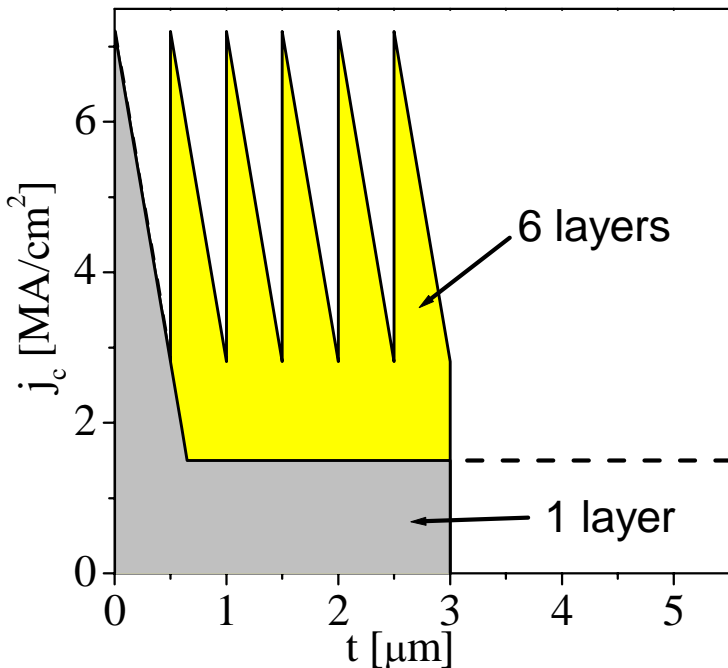
Faster decay with H (not shown):

- Additional defects are large and scarce.

# Our in-field studies impose additional constraints on the possible origin of the stronger pinning in thinner films

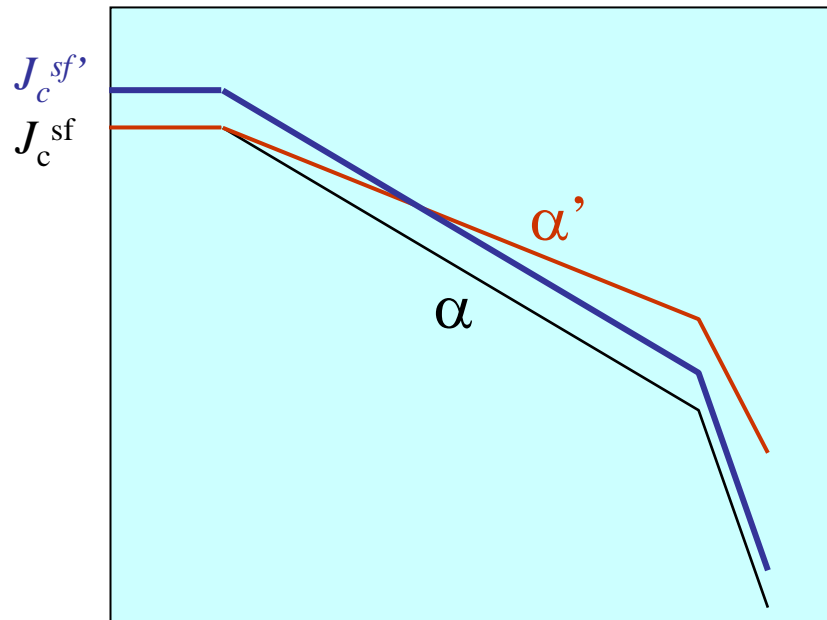


# Multilayers retain high self-field $J_c$ of thin films by resetting the interface-induced pinning. What happens in field?



- Higher  $J_c^{\text{sf}}$  (e.g. multilayers) (without increasing  $\alpha$ )
- Lower  $\alpha$  (without decreasing  $J_c^{\text{sf}}$ )

The real goal is to improve  $J_c$  at technologically relevant  $H$  and  $T$



Context:  
what is the field dependence  
of single layer PLD films?

# $\alpha$ values are robust for given film deposition parameters and can be used as a characterization tool

$\alpha$  for PLD YBCO:

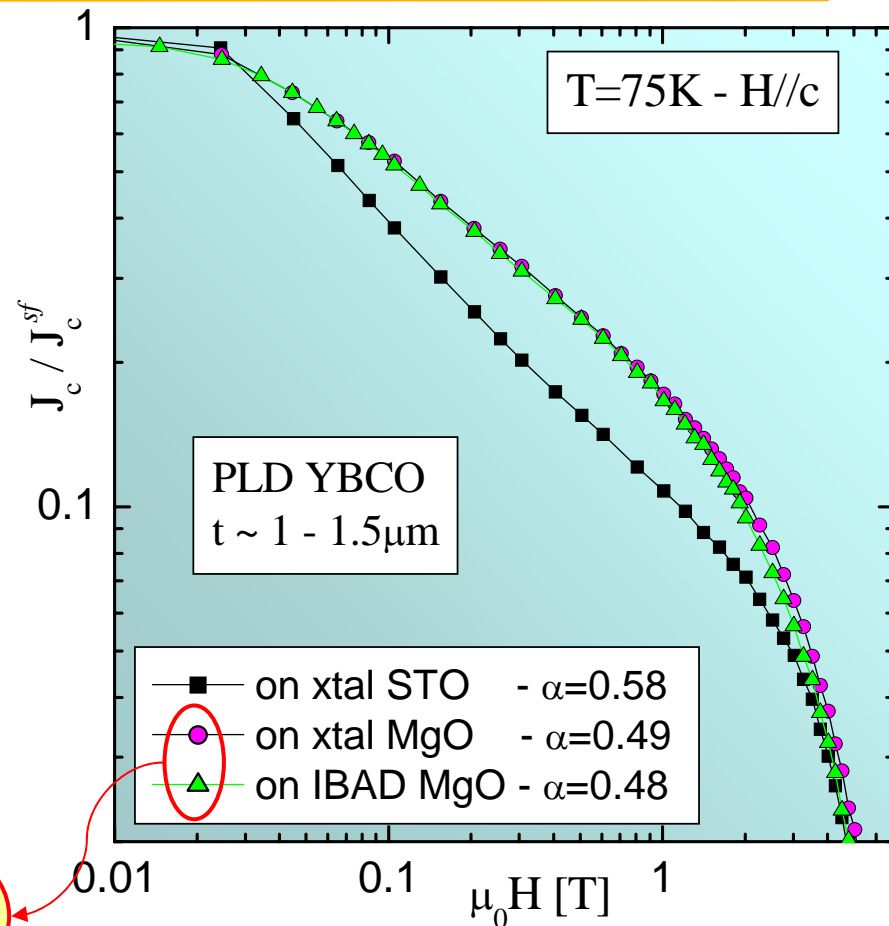
on xtal STO  $\sim 0.6$

on buffer STO  $\sim 0.45 - 0.55$

(consistent for many samples)

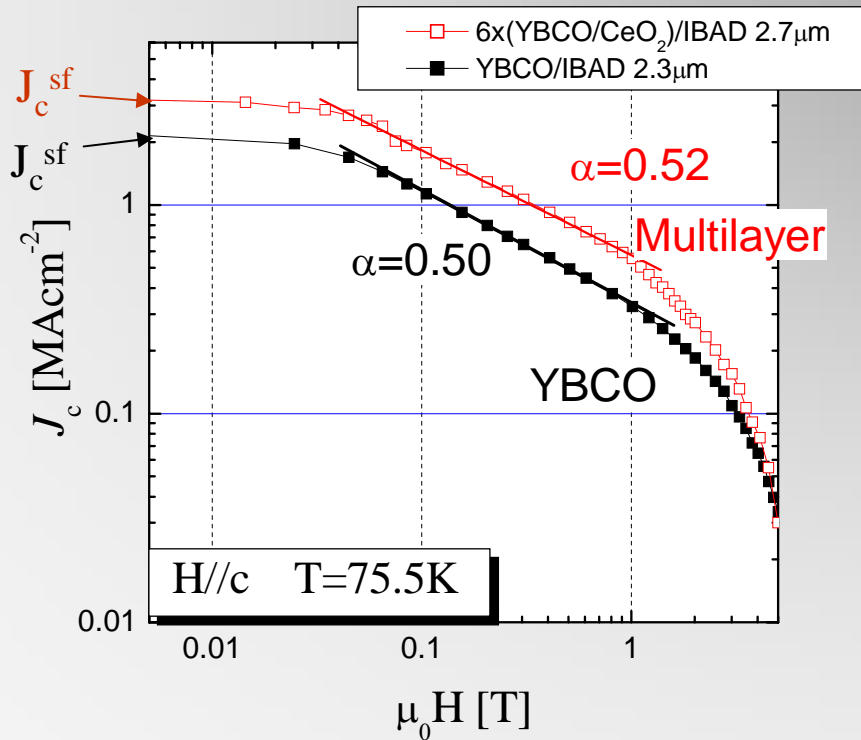
Last year we showed that:

- Lower  $\alpha$  on STO buffer is due to pinning by dislocations associated with STO outgrowths.
- $\alpha$  as low as  $\sim 0.4$  can be obtained by reducing STO deposition temperature, but at the price of reducing  $J_c^{sf}$

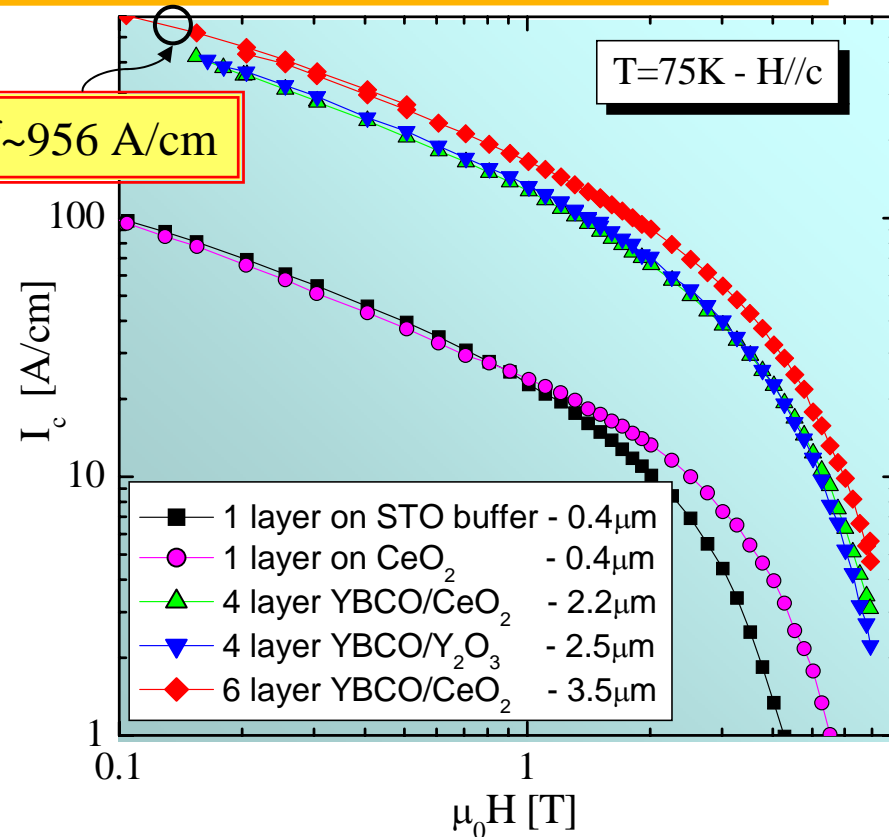


STO  
buffered

# YBCO/CeO<sub>2</sub> multilayers: *in-field* $J_c$ increases due to higher $J_c^{sf}$ with no deterioration in $\alpha$



$$I_c^{sf} \sim 956 \text{ A/cm}$$

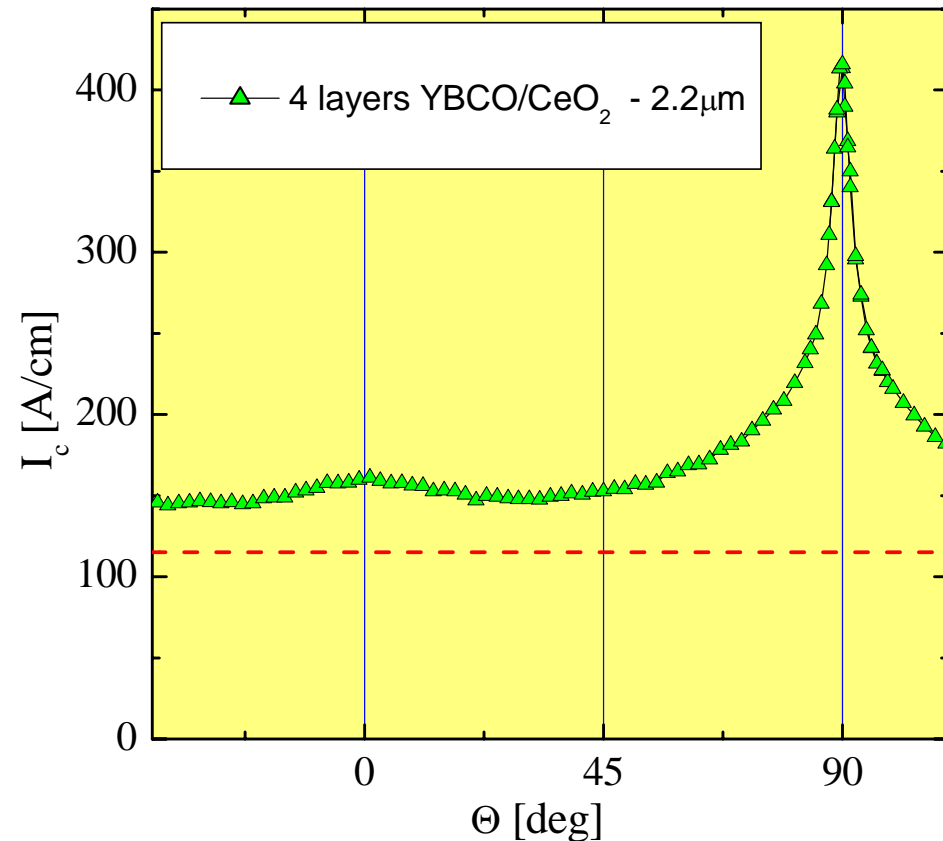
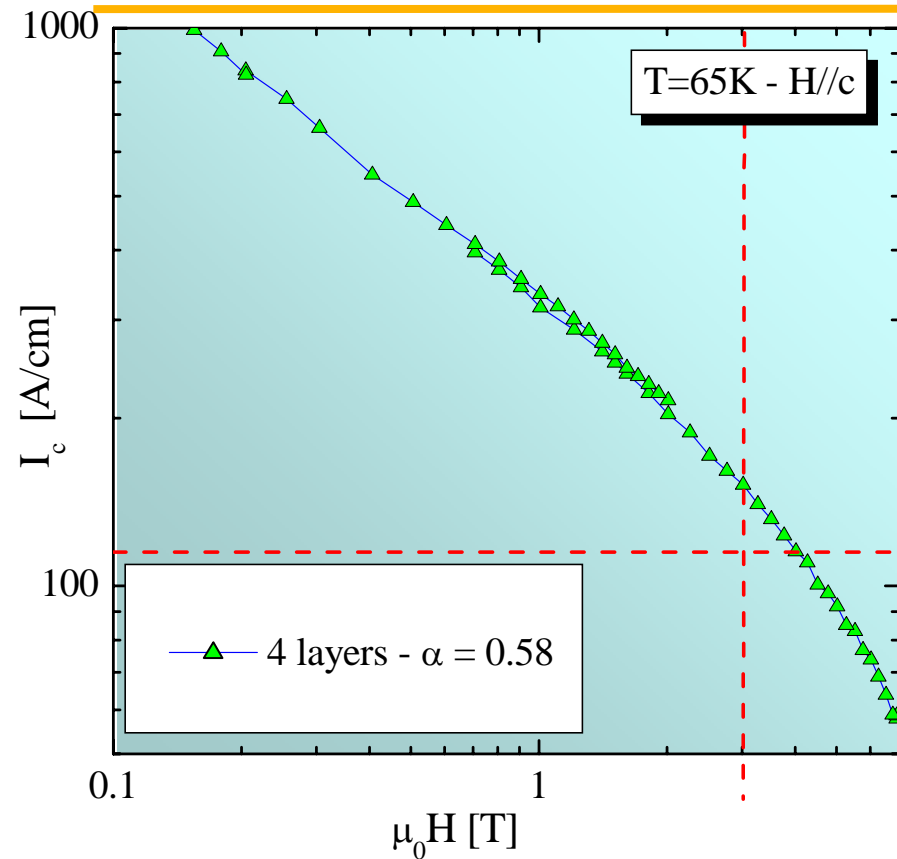


$$J_c^{sf}(\text{YBCO}) = 2.1 \text{ MAcm}^{-2}$$

$$J_c^{sf}(\text{YBCO/CeO}_2) = 3.25 \text{ MAcm}^{-2} (\sim 880 \text{ A/cm})$$

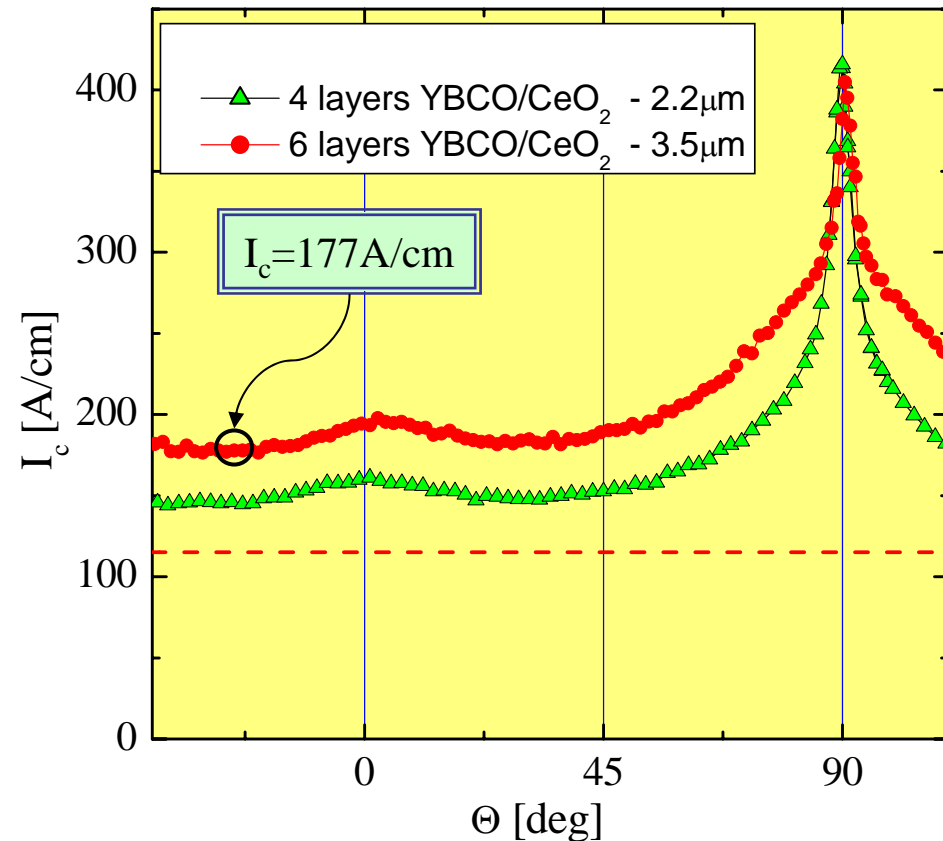
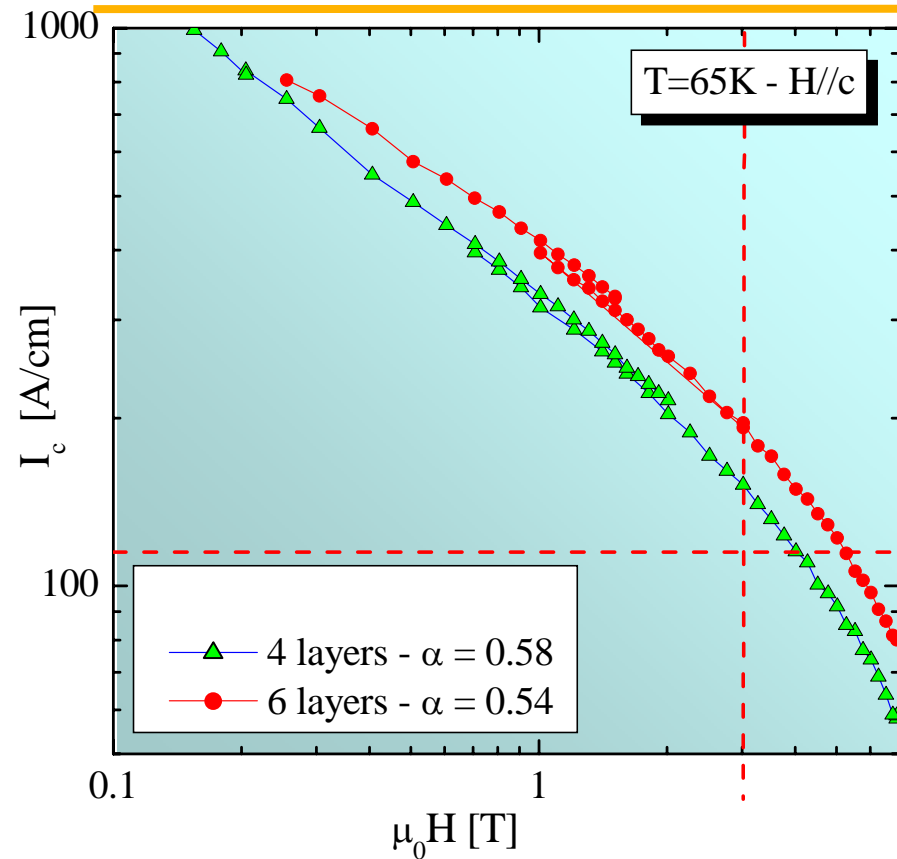
- Same field dependence for 1, 4 and 6 layers
- Same field dependence for CeO<sub>2</sub> and Y<sub>2</sub>O<sub>3</sub> interlayers

# The 2.2 $\mu\text{m}$ thick multilayer comfortably exceeds the target of 115 A/cm at 65K and 3T, worst orientation (DoD Title 3 goals)\*



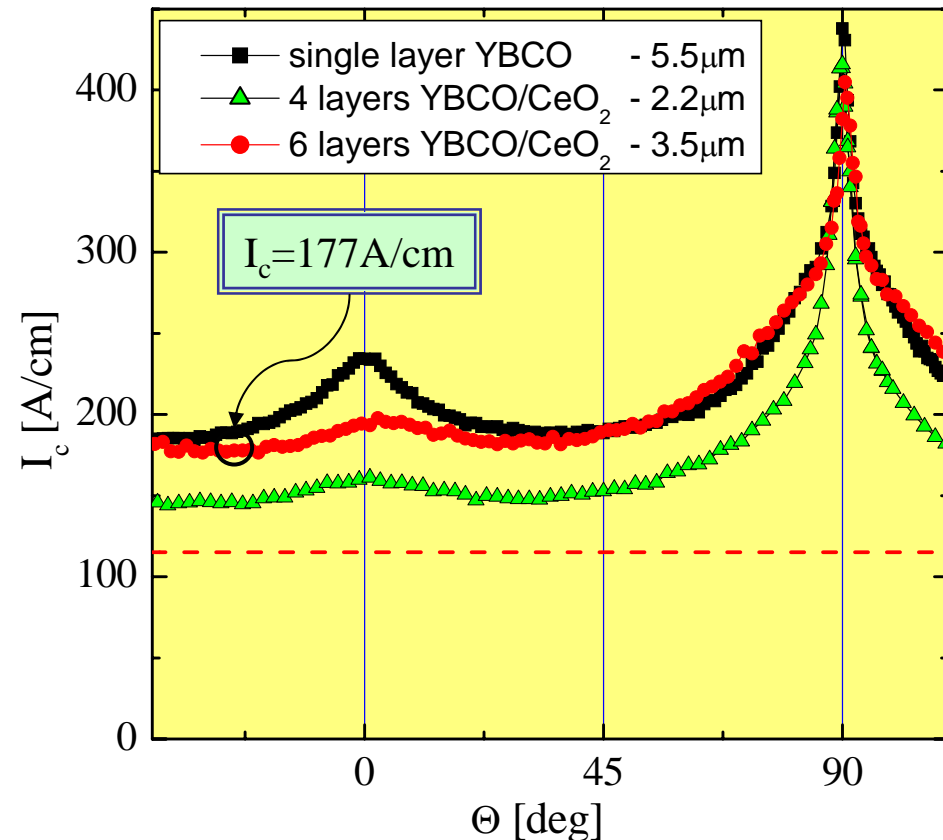
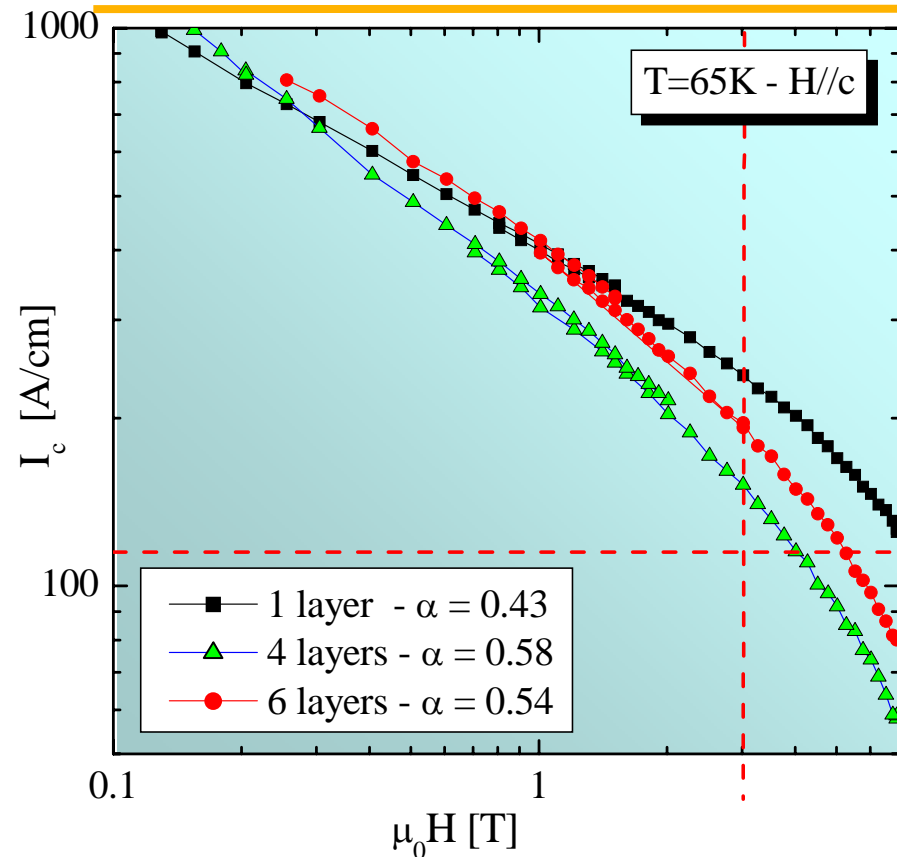
\*as calculated by AMSC,  
Xiaoping Li presentation,  
Wire Workshop January 2005

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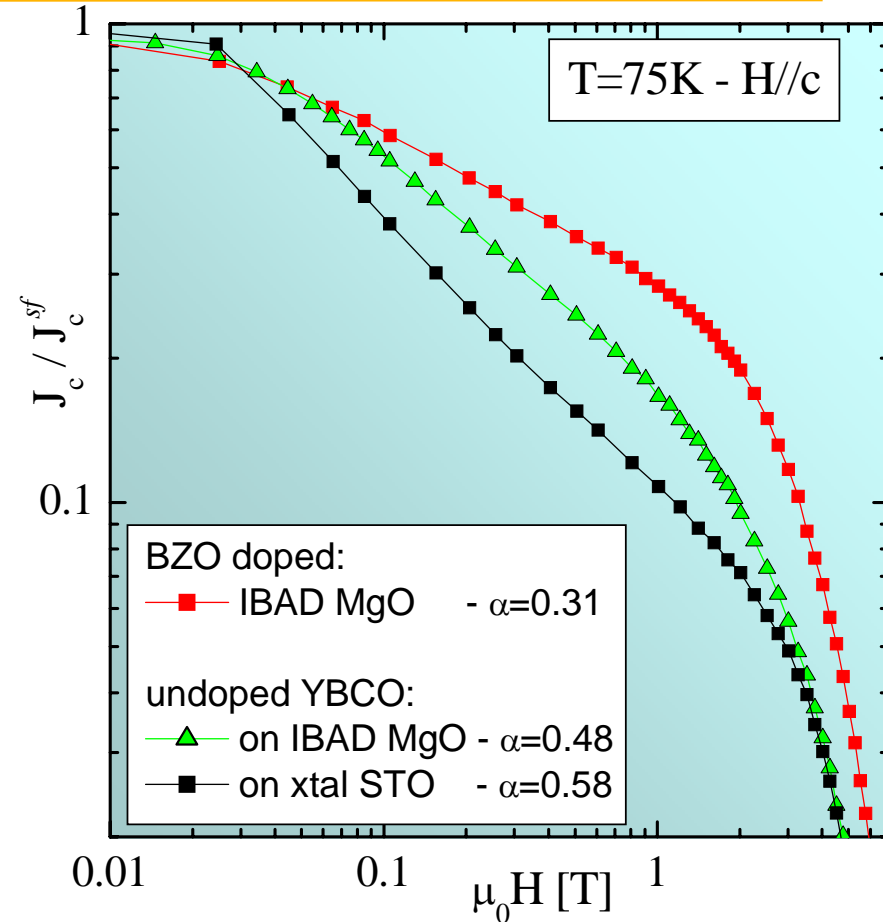
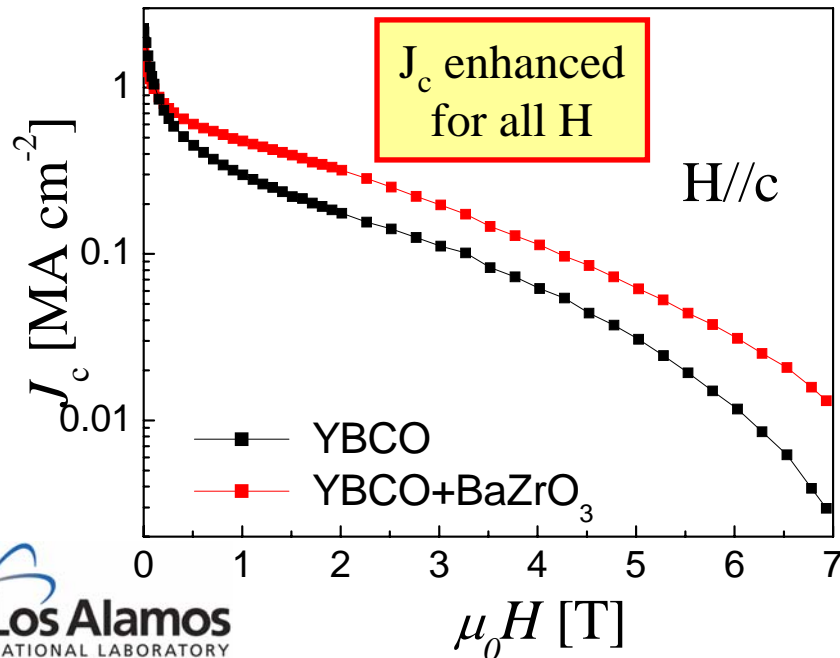
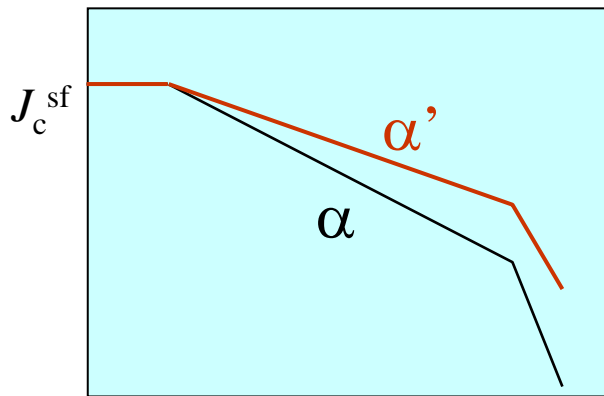
# The 2.2 $\mu\text{m}$ thick multilayer comfortably exceeds the target of 115 A/cm at 65K and 3T, worst orientation (DoD Title 3 goals)\*



a thick enough PLD single layer (5.5 $\mu\text{m}$ )  
with low enough  $\alpha$  (0.43, STO outgrowths)  
also exceeds the requirement

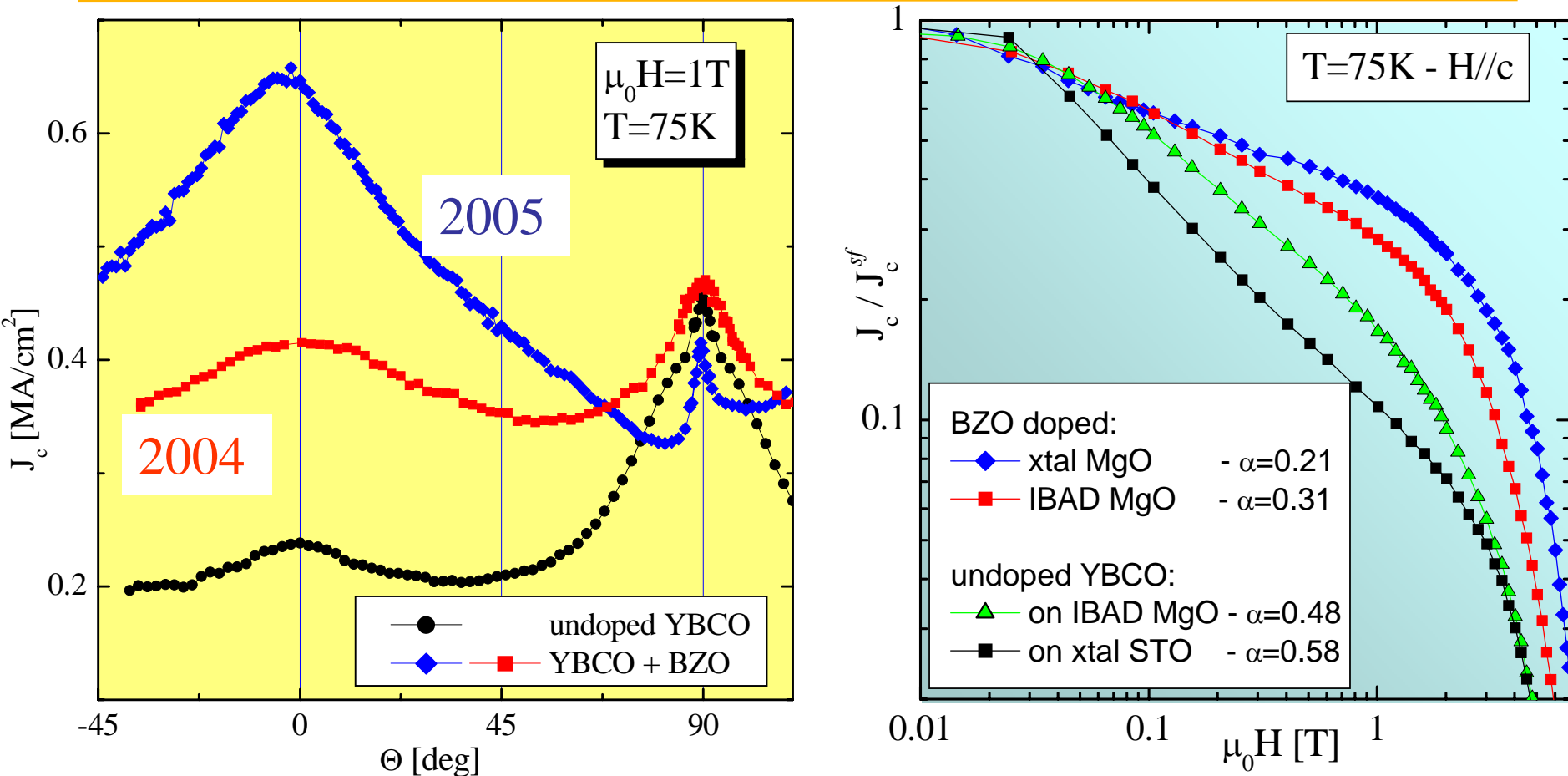
\*as calculated by AMSC,  
Xiaoping Li presentation,  
Wire Workshop January 2005

Last year we showed that doping with BaZrO<sub>3</sub> nanoparticles results in smaller  $\alpha$  and no significant decrease in  $J_c^{sf}$

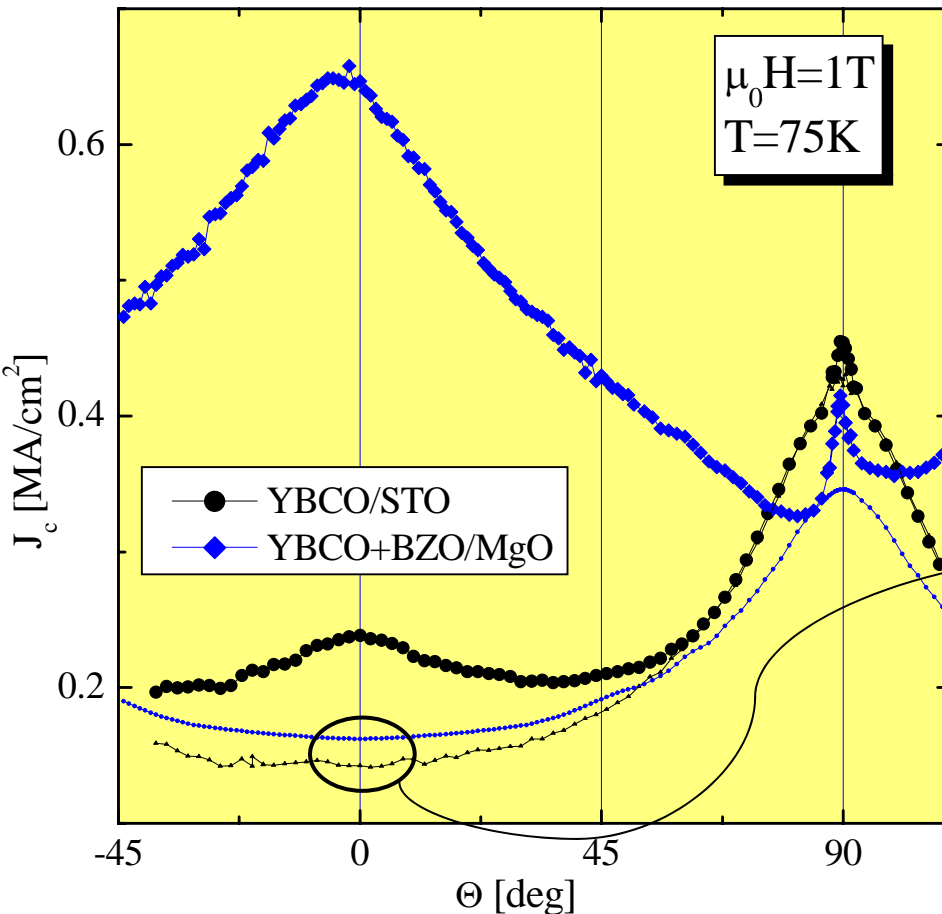


J.L. MacManus-Driscoll *et al.*  
Nature Materials **3**, 439 (2004)

We have now obtained record low field decay with  $\alpha \sim 0.20$   
 This is directly related to a very large c-axis peak



# $J_c$ is dominated by additional c-axis correlated defects (dislocations): anisotropy can be reversed!



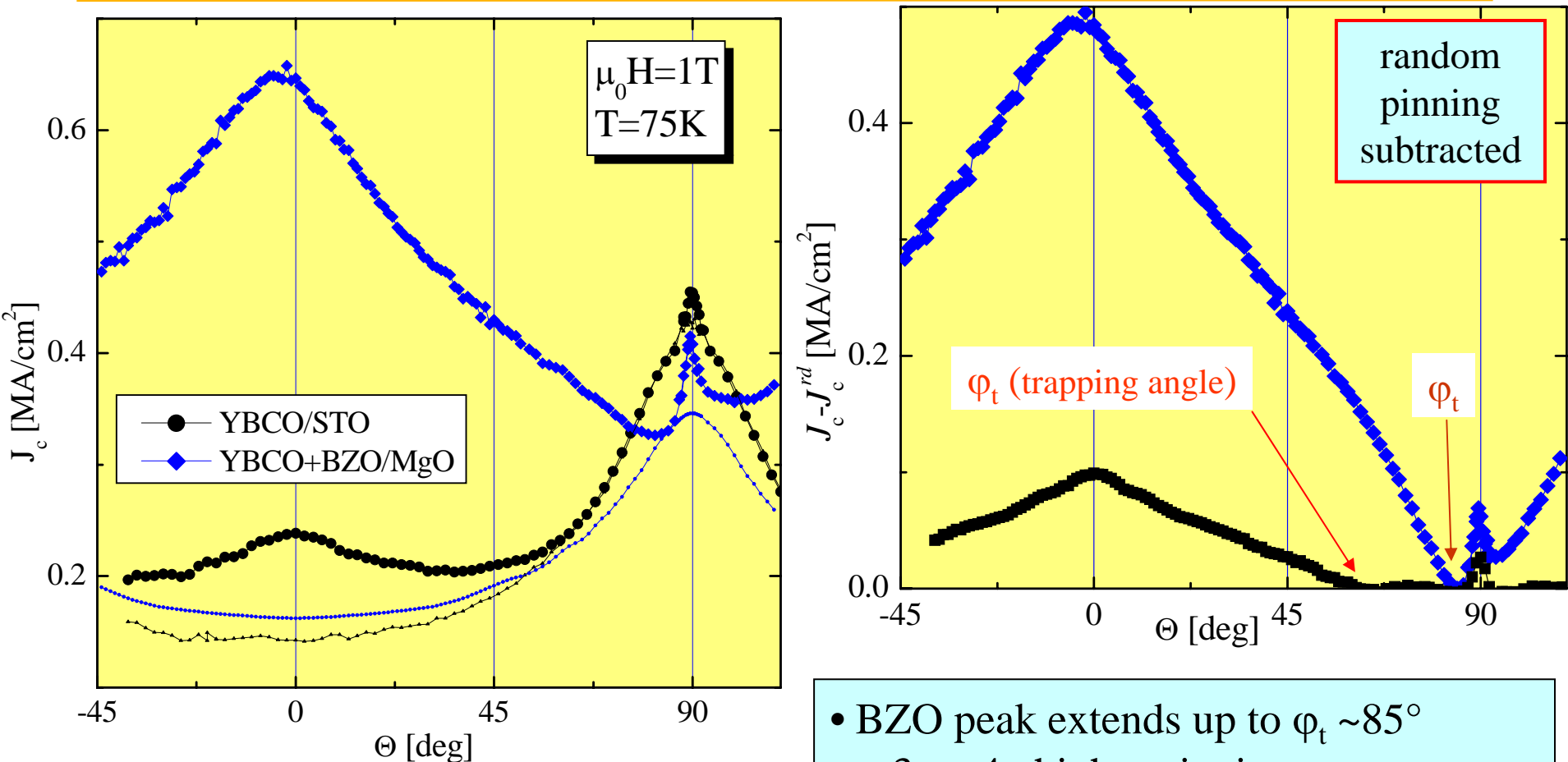
$$J_c(H//c) > J_c(H//ab)$$

“natural”  $J_c$  anisotropy can be reversed  
*without deterioration of  $J_c(H//ab)$*

Random Pinning Component  
(from anisotropic scaling)  
similar to undoped PLD YBCO

small pinning contribution of  
 $BaZrO_3$  particles by themselves

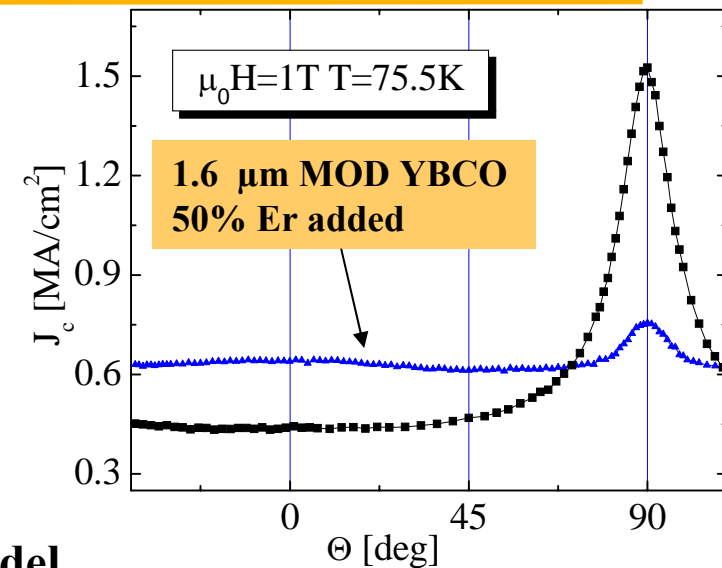
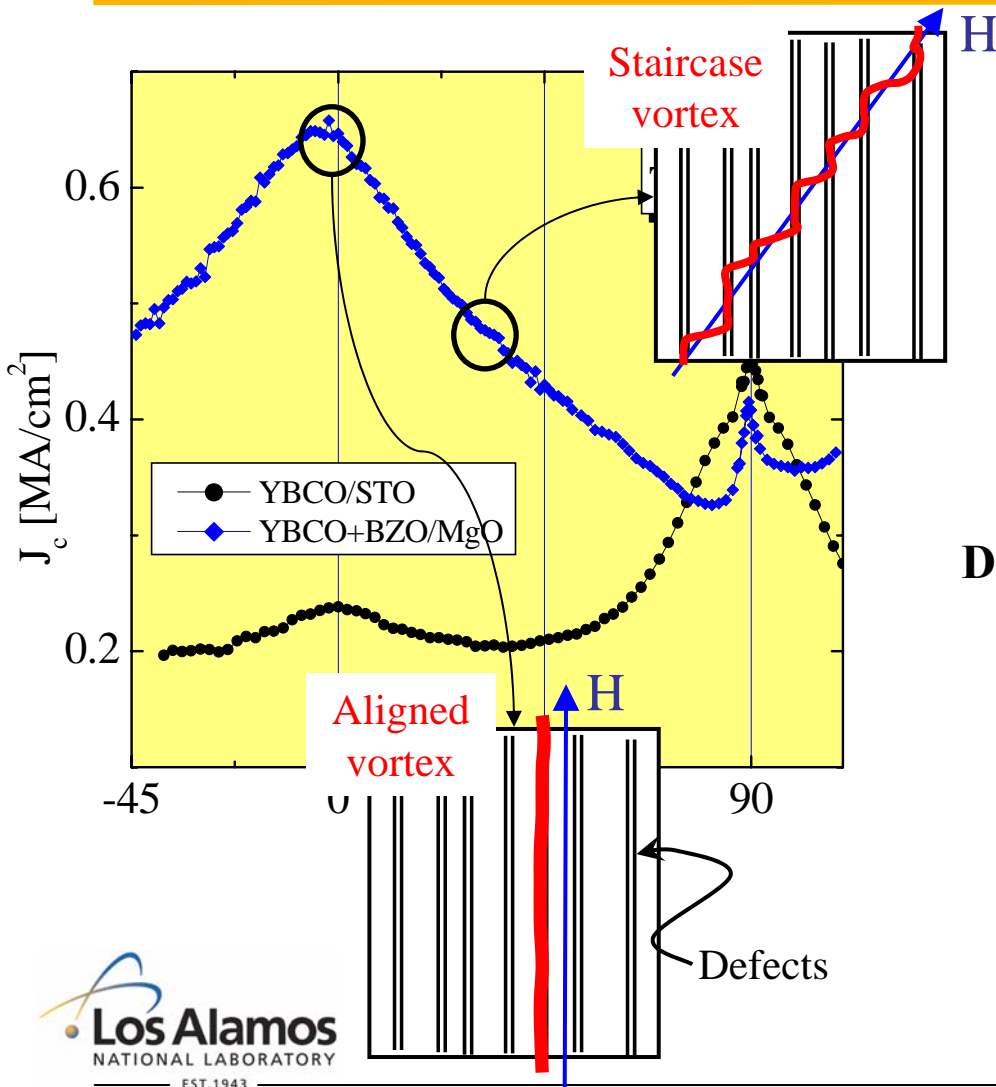
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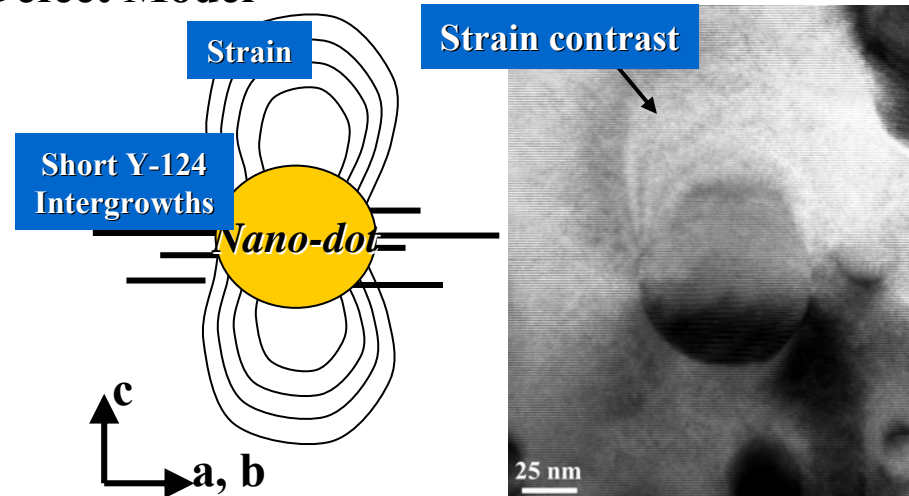
- BZO peak extends up to  $\varphi_t \sim 85^\circ$
- $\sim 3x - 4x$  higher pinning energy
- Same peak as standard YBCO at  $H//ab$

# BZO nanoparticles in PLD: aligned defects//c-axis

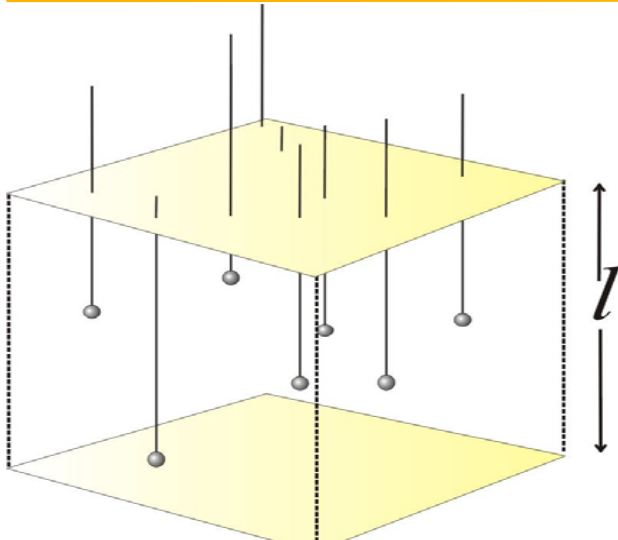
## Nanodots in Er-added MOD: strain field (splayed-like)



### Defect Model



# The density of c-axis correlated defects (dislocations) can be estimated from TEM images

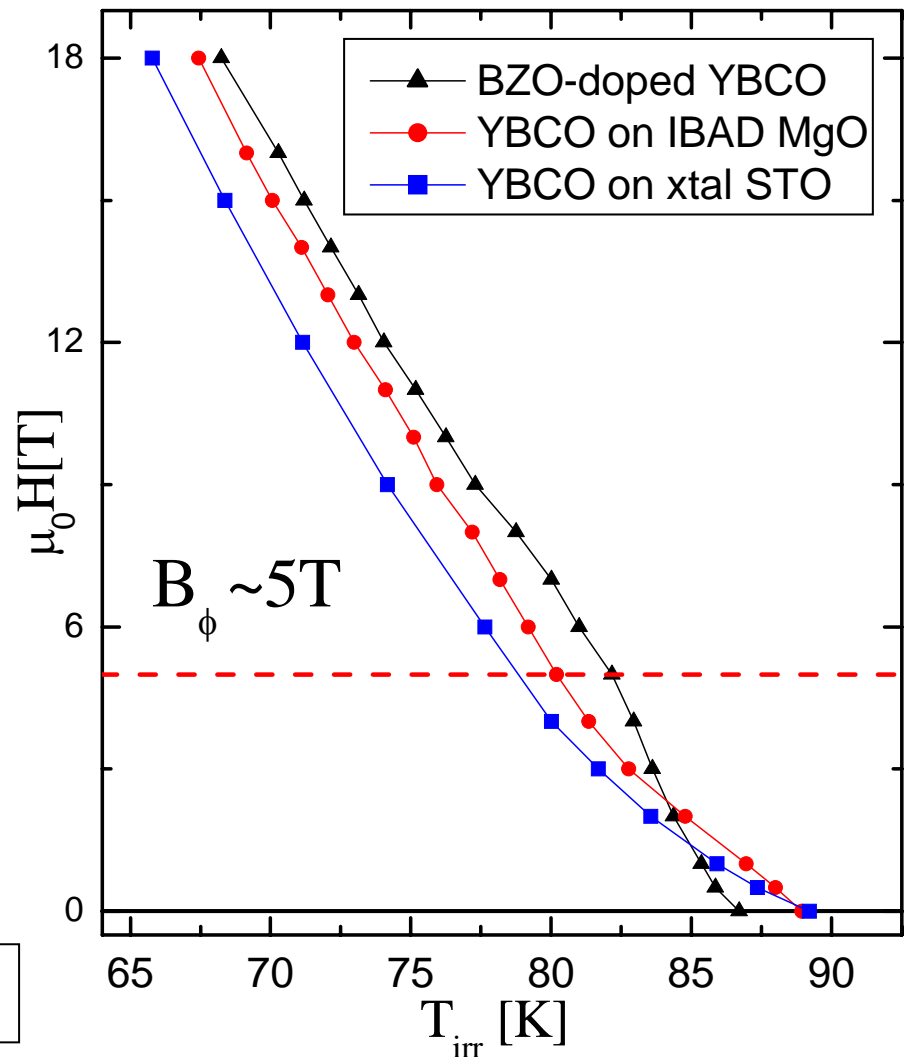


Mean dislocation distance  $d \sim 40\text{nm}$

Mean dislocation length  $l \sim 120\text{nm}$

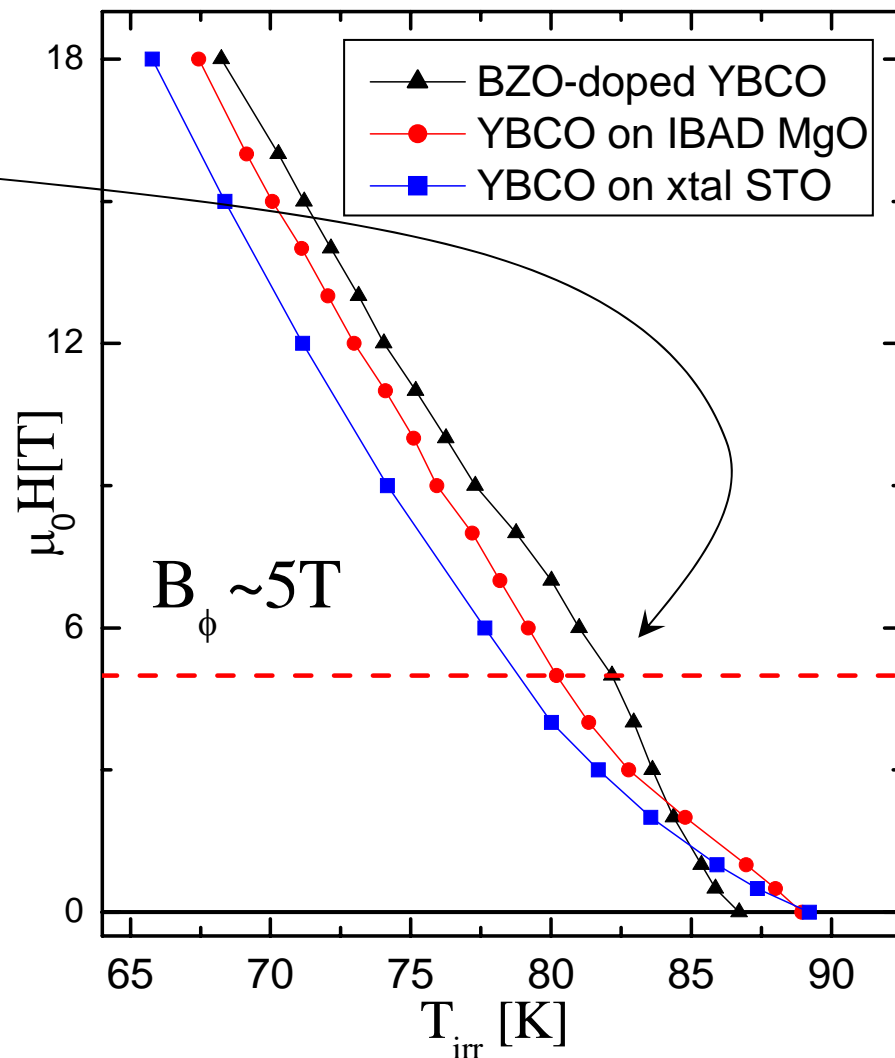
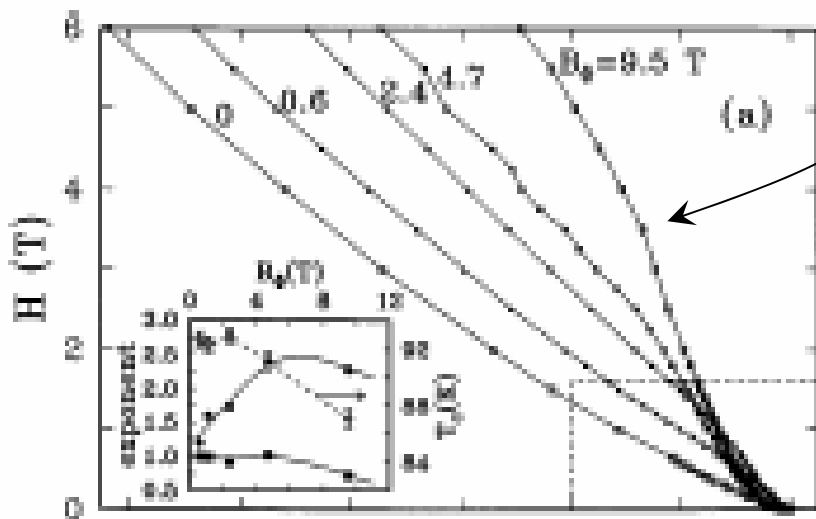
- The number of dislocations that cross an ab-plane per unit area is the “matching field”  $B_\phi$

$$B_\phi = \phi_0 (1/d)^3 l \sim 4 \text{ T}$$

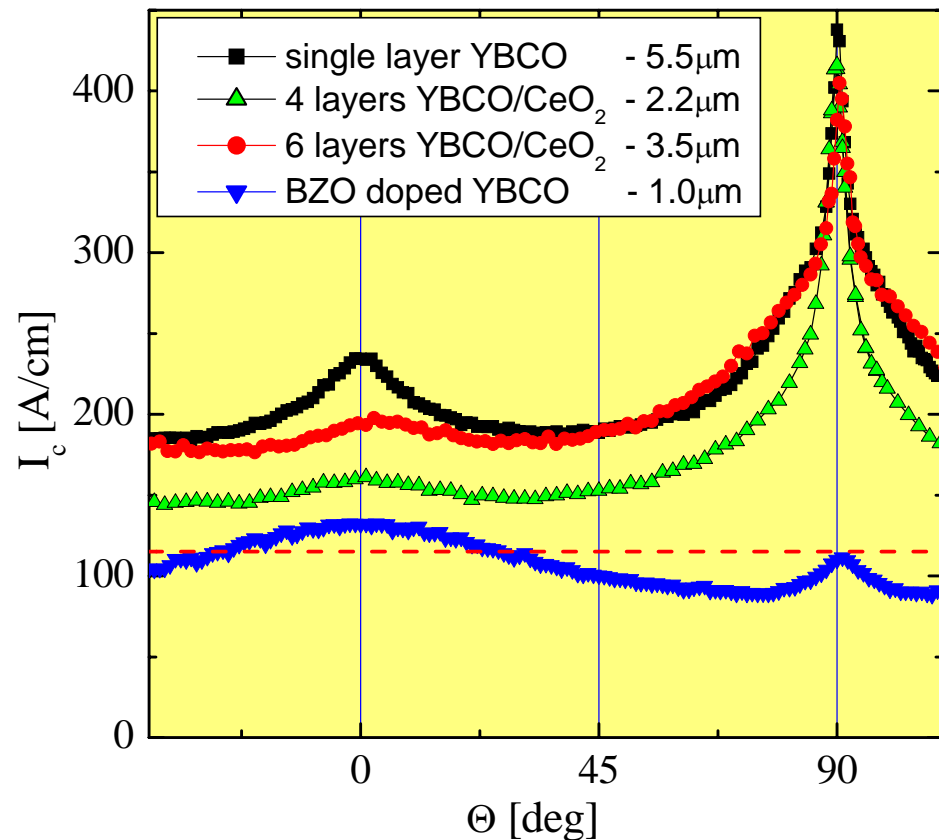
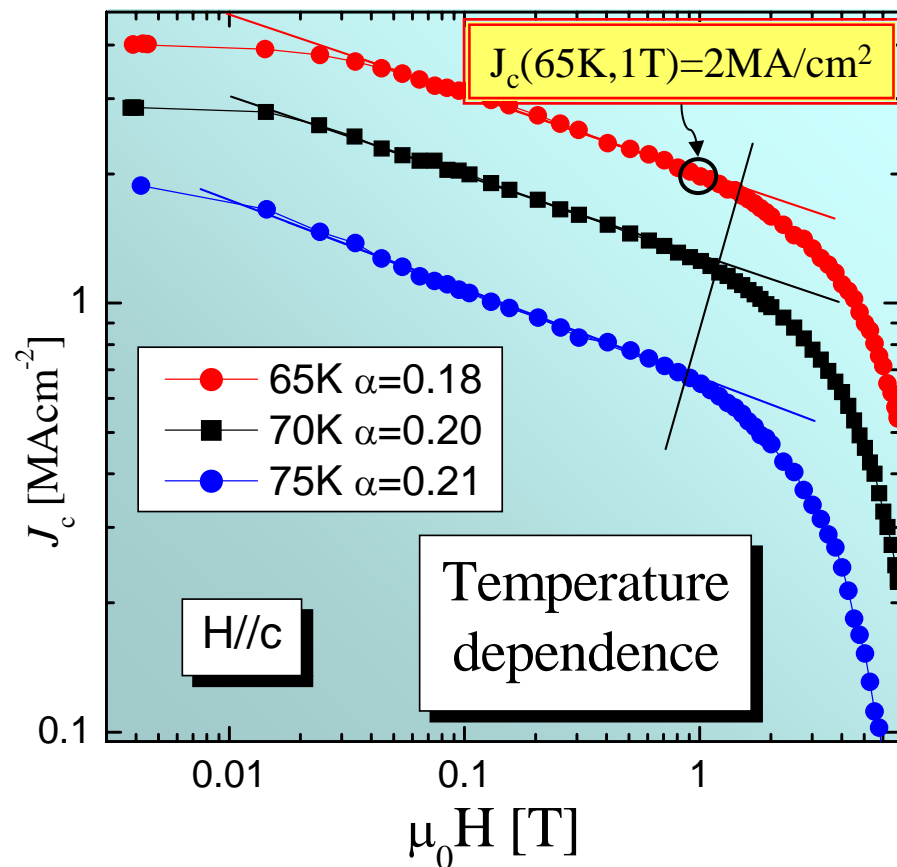


# As in the case of columnar defects made by heavy-ion irradiation, these dislocations increase the irreversibility line

“bump” characteristic of correlated defects allows estimate of  $B_\phi$

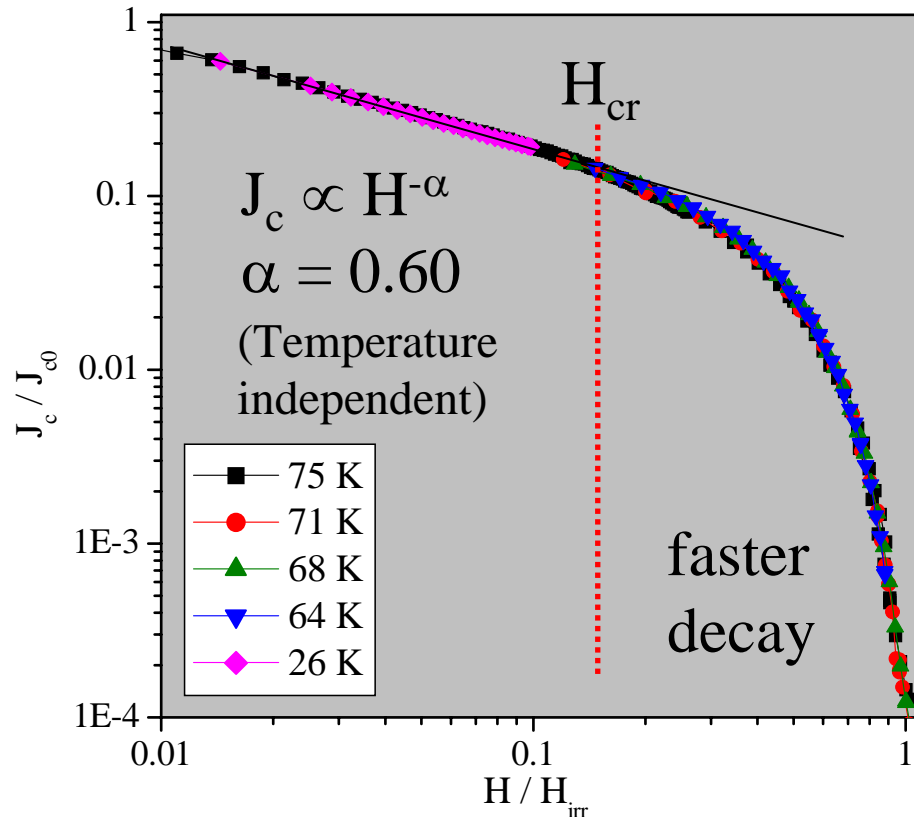


# The record low $\alpha$ of the BZO-doped PLD YBCO is maintained at lower temperature



**Target of 115 A/cm at 65K and 3T (worst orientation) almost achieved by a 1  $\mu\text{m}$  film !!!**

# Transport measurements at 26K (in liquid Ne) give same $\alpha$ values as those obtained at 65K-75K



However, several open questions remain:

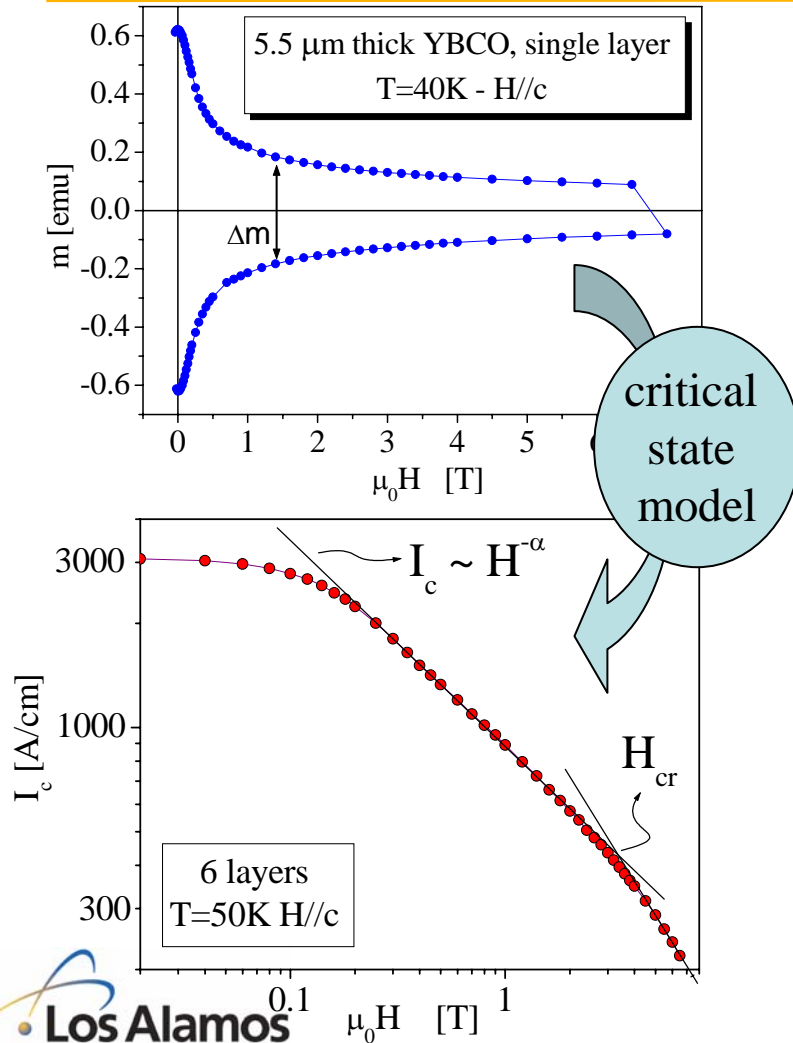
- What happens in the technologically relevant 30K-50K range?
- What is the temperature dependence of  $H_{cr}$  ?

From a practical perspective:

Transport measurements in liquid Ne are slow and expensive, with risk of sample damage due to contacts heating

We decided to incorporate a complementary technique:  
determination of  $J_c$  by magnetization

# Magnetization measurements of $J_c$ allows us to explore the whole temperature range from 4K to $T_c$



Additional advantages:

- Fast (no patterning required)
- No risk of sample damage

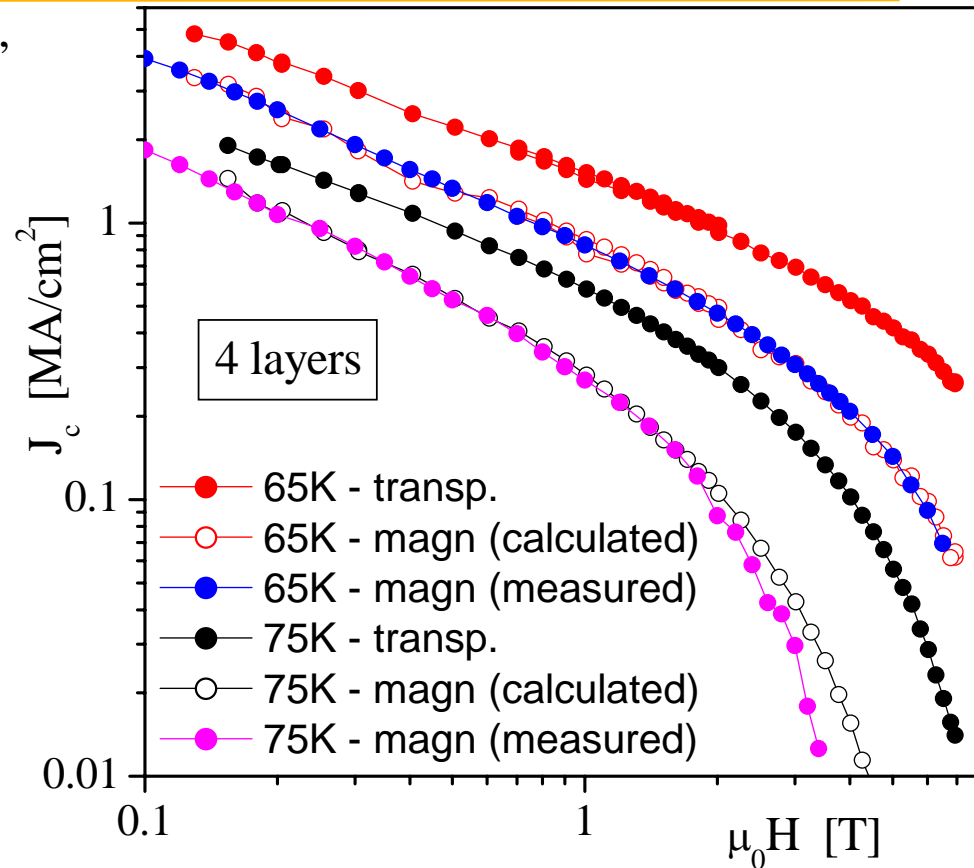
How well do transport and magnetization values of  $J_c$  compare?

Complication:

- Magnetization has an equivalent “voltage criterion” of  $\sim 10^{-10} - 10^{-11}$  V/cm, several orders of magnitude lower than transport ( $10^{-6}$  V/cm)
- So, magnetic  $J_c$  is lower than transport  $J_c$ . The difference is significant for low  $N$  in the  $V \sim I^N$  curves

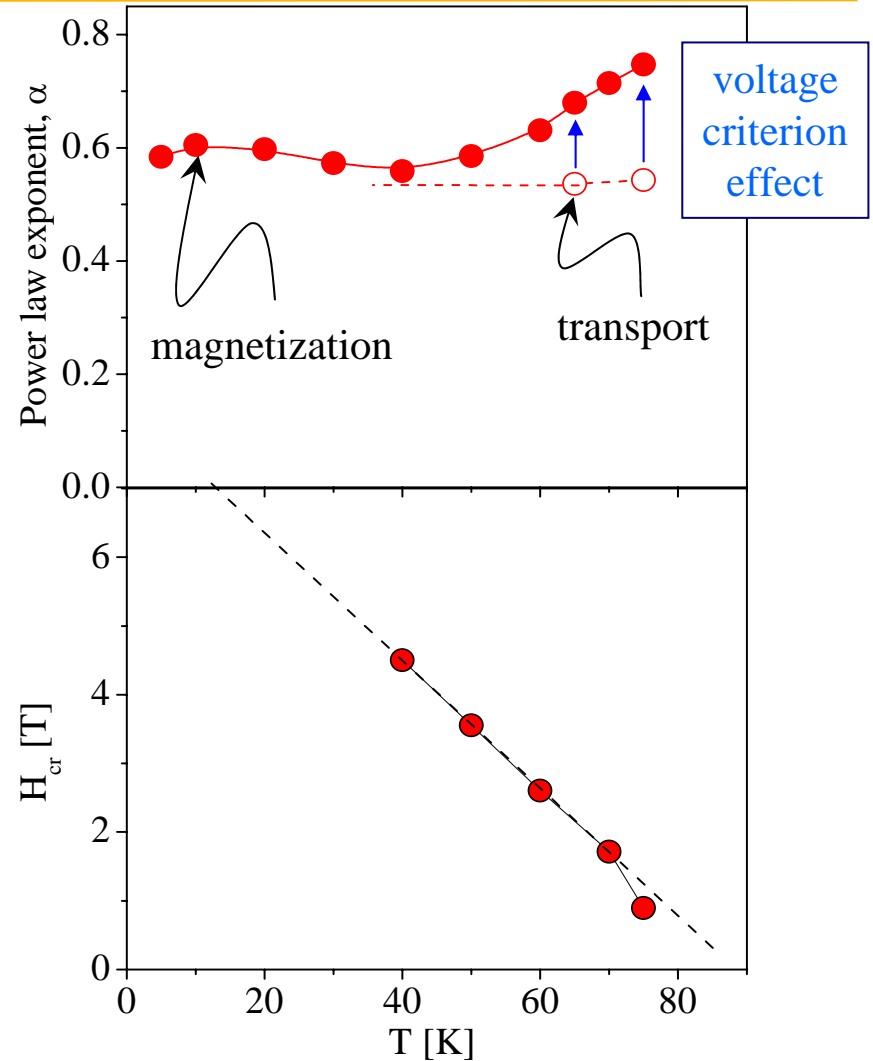
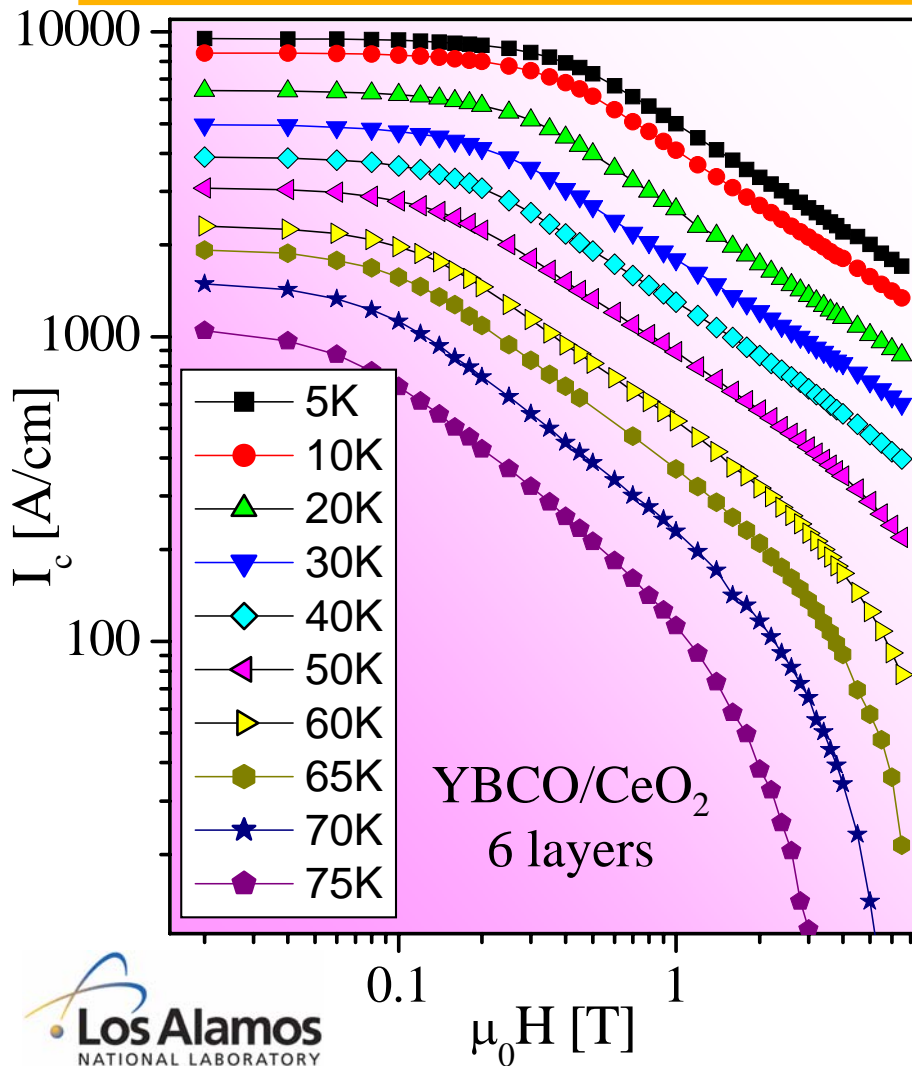
# Magnetization and transport measurements of $J_c$ show excellent agreement if voltage criterion effect is corrected

- Transport  $J_c$  corrected by “voltage criterion” coincides with magnetization results.
- For large  $N$  (low  $H$ ) the correction is minor.
- The difference increases as  $N$  decreases (field increases).
- Magnetization  $\alpha$  is higher than transport  $\alpha$ , the difference is small and systematic.
- $J_c$  and a magnetization values can be safely compared among samples.

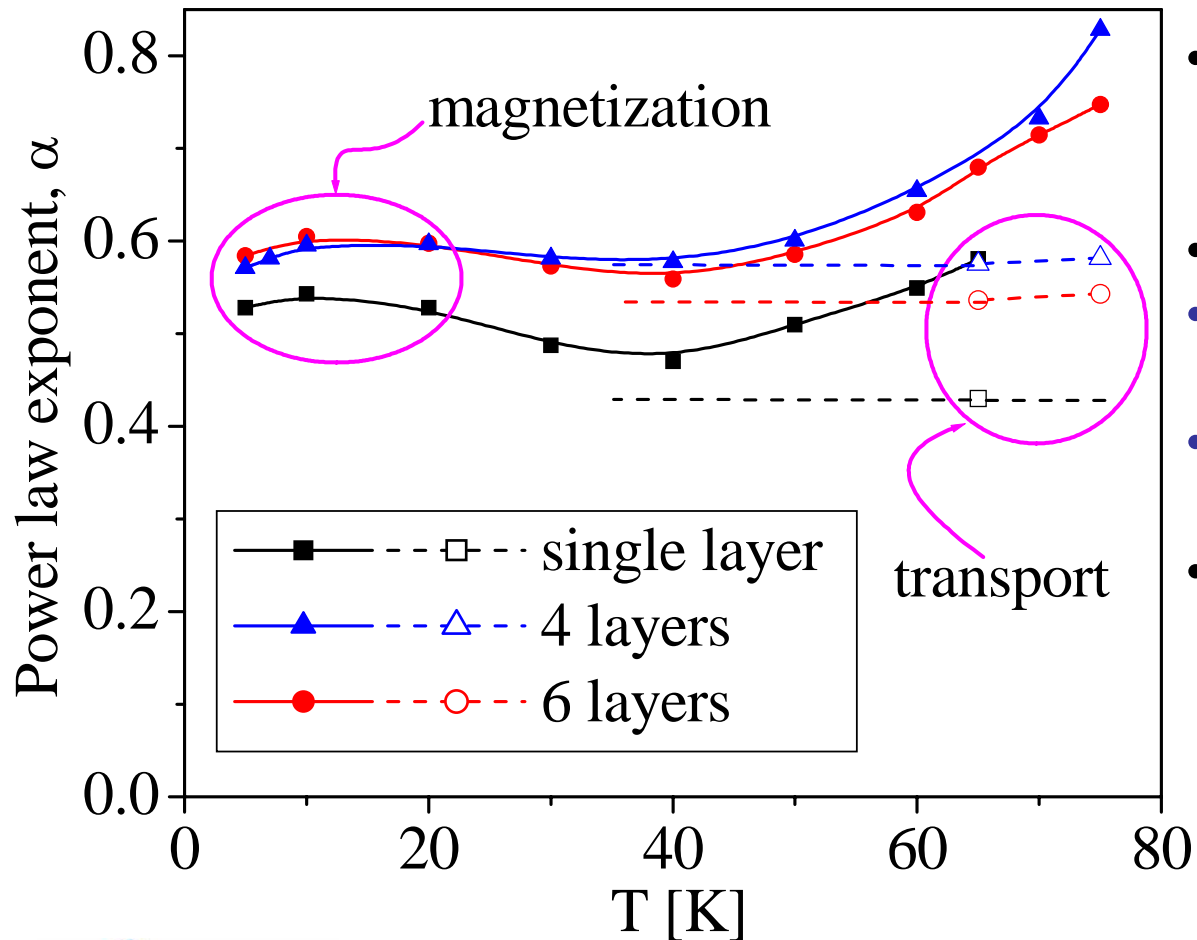


We will always show real (not corrected) magnetization results.  
Magnetization  $J_c$  is equal to or lower than transport  $J_c$

# We can obtain maps of $J_c$ , $\alpha$ and $H_{cr}$ over large T-H regions

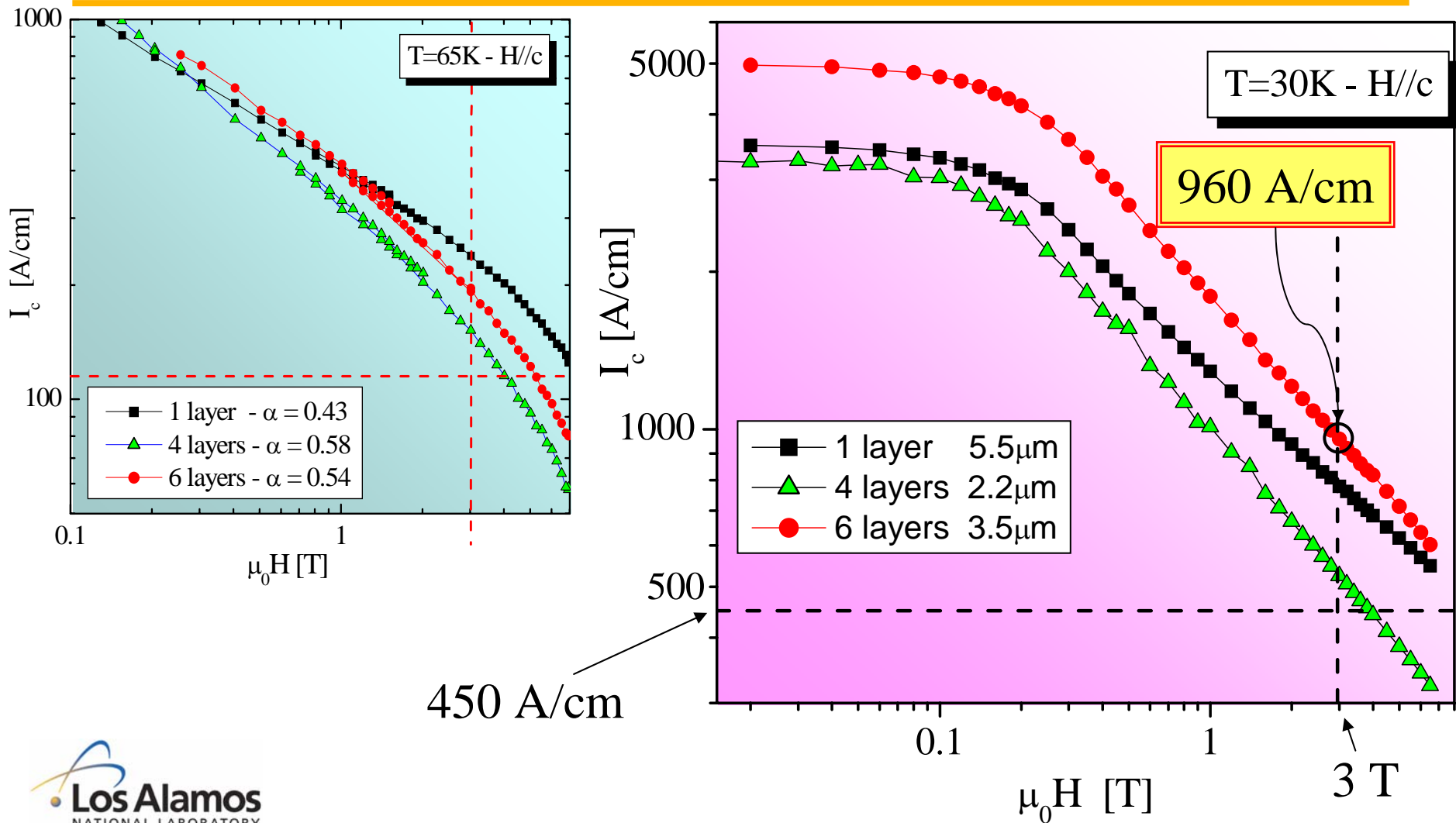


# $\alpha$ in undoped YBCO (single- and multilayer) is *almost* temperature independent



- differences at high  $T$  due to voltage criterion effect
- comparison transp. vs magn.:
  - very good agreement for variations among samples
  - good numerical agreement
- variations of  $\alpha$  with  $T$  are small but systematic

# The multilayers (and the thick single layer) also exceed the DoD Title 3 target of 450 A/cm at 30K and 3T



## Scoring criterion -- Results

1. Validated incremental  $j_c$  model by ion milling.
2. Developed tools – such as PrBCO/YBCO bilayers – for further analysis of thickness dependence.
3. Measured the thickness dependence as a function of  $T$ ,  $H$  and  $\Theta$ .
4. Significantly narrowed possible explanations for thickness dependence of  $J_c$ .
5. Found a “smoking gun” for interfacial effects in misfit dislocations.
6. Determined that the defects responsible for additional pinning in thin films are uncorrelated and scarce.
7. Demonstrated that multilayers retain high  $I_c$  performance in field.
8. Surpassed all DoD Title 3  $I_c$  milestones
9. Found record low field decay of  $J_c$  in BaZrO<sub>3</sub>-doped films.
10. Introduced new tools (such as magnetization and high-field irreversibility line) for further exploration of vortex pinning.

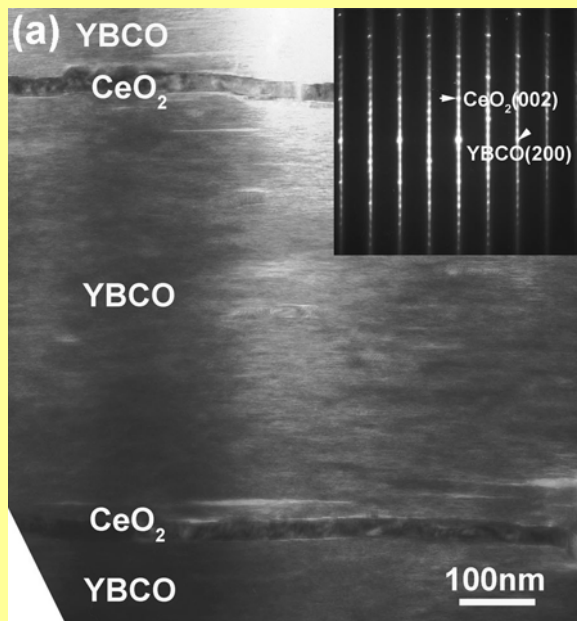
## Scoring criterion -- FY2005 Performance

Assist industrial partners in implementing multilayer designs appropriate to their deposition technologies.

- ➔ Multilayers were regularly discussed with SuperPower during site visits and conference calls.
- ➔ SuperPower has decided to utilize multilayers in their MOCVD/IBAD MgO process, and has successfully demonstrated multipass YBCO – a necessary step.
- ➔ Samples were exchanged for process optimization and advanced characterization at Los Alamos.
- ➔ We have successfully demonstrated the use of  $Y_2O_3$  interlayers, which will facilitate incorporation of multilayer technology into the MOCVD process.

# Scoring criterion -- FY2005 Performance (continued)

Continue to refine multilayers to exploit very high  $J_c$ s for thinner YBCO.  
*Goal: Reproducible 1000 A/cm-width in 2.5  $\mu\text{m}$ .*



With our typical layer thickness of  $\sim 0.6 \mu\text{m}$ :

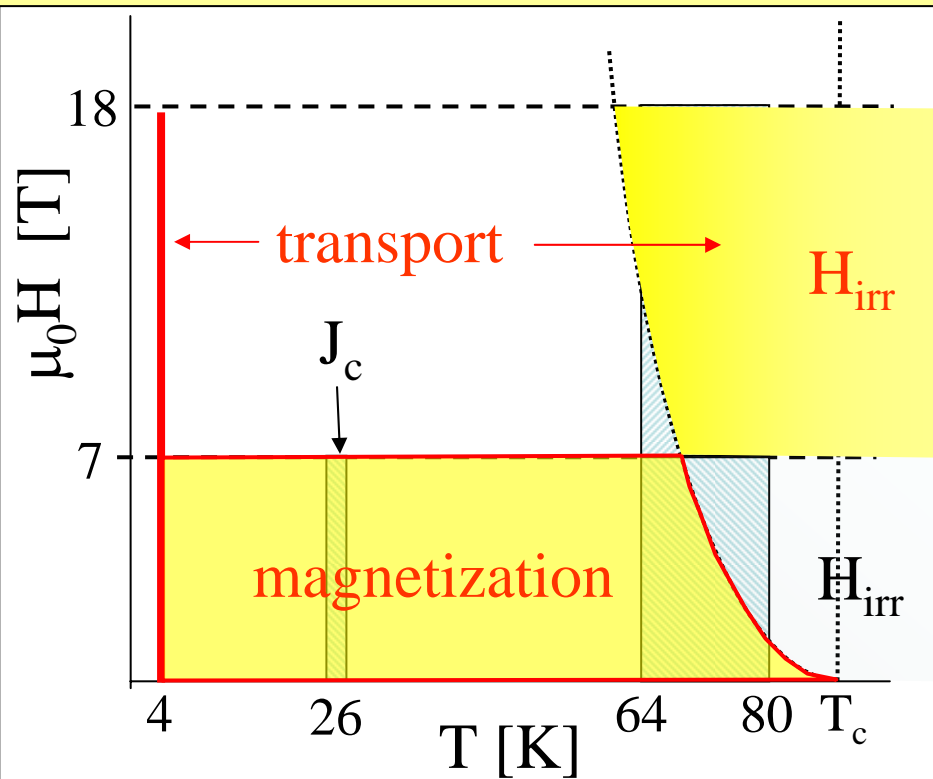
- 880 A/cm-width, 2.2  $\mu\text{m}$ , 4 YBCO layers
- 890 A/cm-width, 2.3  $\mu\text{m}$ , 4 YBCO layers
- 900 A/cm-width, 2.5  $\mu\text{m}$ , 4 YBCO layers\*  
\*(first test of Y<sub>2</sub>O<sub>3</sub> interlayer)

Promising result with thinner YBCO:

- 385 A/cm-width, 0.7  $\mu\text{m}$ , 2 YBCO layers  
(5.5 MA/cm<sup>2</sup>)

# Scoring criterion -- FY2005 Performance (continued)

Improve our liquid Ne (26K) measurement capabilities.  
*Goal: 5 fold throughput increase.*

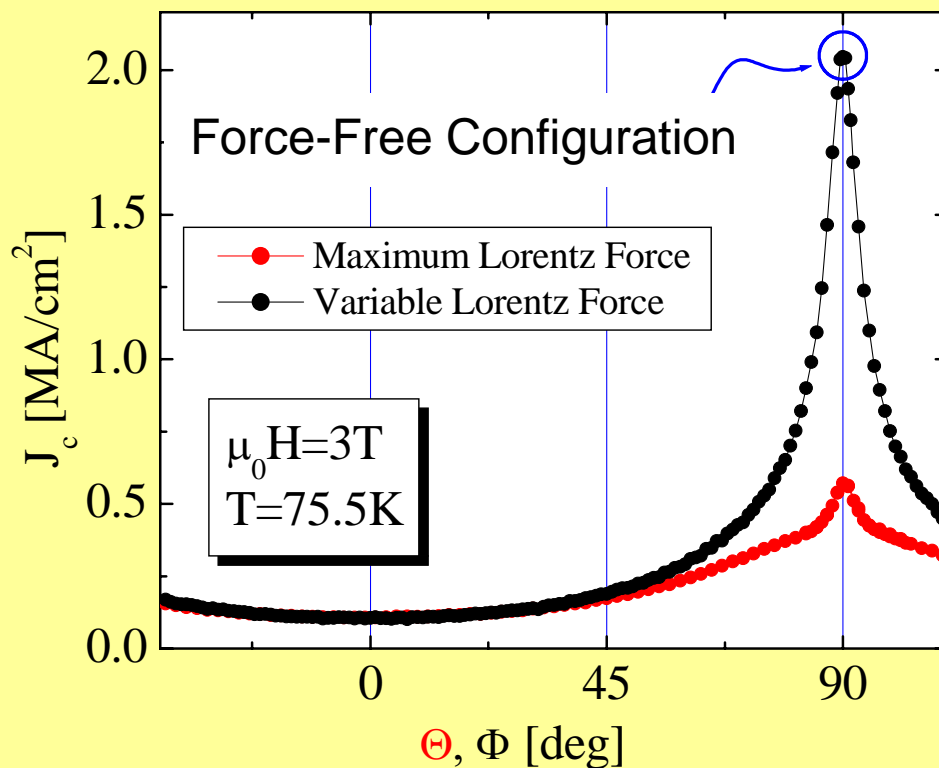


We modified and expanded this goal:

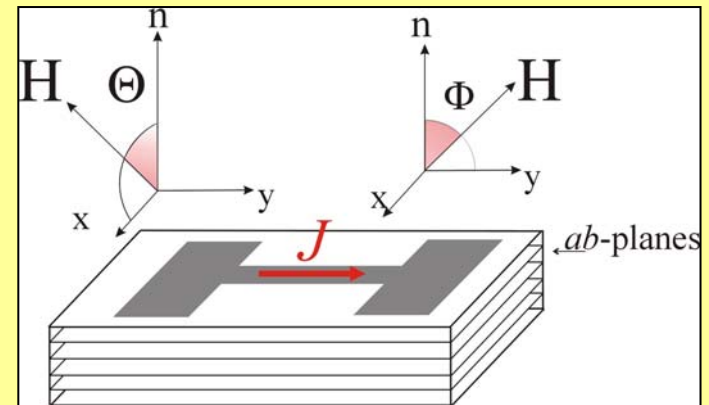
- $J_c$  from magnetization 4K to  $T_c$  – up to 7T (throughput 3-5 samples/week)
- $J_c$  from transport, 4K, up to 18T
- $H_{irr}$  from transport, up to 18T

# Scoring criterion -- FY2005 Performance (continued)

Extend angular dependent measurements to non-maximum Lorentz force configurations.  
*Goal: understanding of pinning and current distribution in realistic situations for applications.*

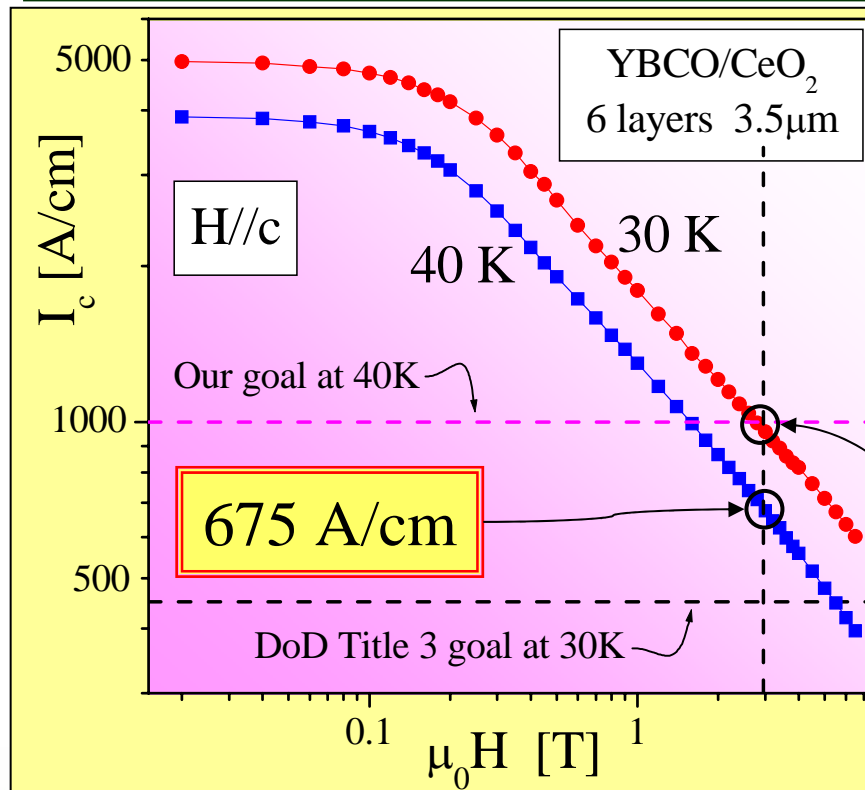


- Variable Lorentz Force configuration offers additional information about
  - percolation (granularity)
  - vortex lattice “stiffness”
- Part of the work in collaboration with J. Durrell and J.E. Evetts (Univ. Cambridge)



# Scoring criterion -- FY2005 Performance (continued)

Continue to study pinning enhancement by nanoparticles, RE substitutions (variance), and YBCO/CeO<sub>2</sub> multilayers (coordinated with S. Foltyn et al.).  
*Goal: 1000 A/cm at 40K, 3T.*



We achieved:

- 960 A/cm-width, at 3T--30K (more than a factor of 2 above DoD goal)
- 675 A/cm-width, at 3T--40K (2/3 of our goal)

## Scoring criterion -- Research integration

- ➔ We have worked closely with SuperPower in many areas (addressed in our CRADA talk yesterday):
  - ✓ Laying the groundwork for transfer of multilayers to their MOCVD-based production process.
  - ✓ Measurement and analysis of temperature, field and orientation dependence of  $J_c$  for pinning improvement in MOCVD CC.
  - ✓ Winding and characterization of coils using IBAD MgO-based tapes.
- ➔ As part of the Wire Development Group, we identified planar defects along the ab planes as the main source of pinning in MOD films from American Superconductor, and explored the pinning effects of RE additions and oxygen treatments (addressed by T. Holesinger in WDG talk Tuesday).
- ➔ We continued our extensive collaboration with the Univ. of Cambridge, UK (J.L. Driscoll, J.E. Evetts, J. Durrell), in the exploration of pinning enhancement routes, vortex dynamics in variable Lorentz force configurations, and characterization of thick films grown by Hybrid Liquid Phase Epitaxy (HLPE)

## Scoring criterion -- Research integration

- We continued our collaboration with the Air Force Research Lab. (T. Haugan, P. Barnes) on the vortex pinning of their 211-based multilayers.
- We have begun a new collaboration with MIT Lincoln Laboratory to aid in a study to see if multilayers can improve the properties of HTS-based microwave filters.
- We began a collaboration with Ron Feenstra (Oak Ridge National Laboratory) to explore angular and field dependent pinning mechanisms in ex-situ films produced by  $\text{BaF}_2$ . (addressed in WDG talk Tuesday).
- We began a collaboration with the group of D. Larbalestier at Univ. of Wisconsin-Madison (summer student-magnetization studies)
- We began a collaboration with Argonne National Laboratory to employ focused ion beam milling to compliment our ion milling experiments.

# Scoring criterion -- FY 2006 Plans

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→ Continue research into the cause of elevated  $j_c$  near the interface.

*Goal: Understand the 0.65  $\mu m$  range of influence.*

→ Survey alternate interlayer or buffer layer materials.

*Goal: Determine which properties are significant in producing high interfacial  $j_c$ .*

→ Push the practical limit to thick-film  $I_c$  that can be achieved by depositing a greater number of thinner YBCO layers.

*Goal: 1000 A/cm-width in a 2  $\mu m$  film.*

→ Combine multilayers with an in-field pinning enhancement method.

*Goal: self-field  $I_c = 1000$  A/cm-width and  $\alpha < 0.4$ .*

## Scoring criterion -- FY 2006 Plans

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➔ Continue to work with American Superconductor in the understanding and enhancement of vortex pinning in ex-situ films.

*Goal: To be coordinated with AMSC.*

➔ Work closely with SuperPower to produce high-current multilayers on IBAD MgO using MOCVD.

*Goal: Significant improvement over single-layer  $I_c$ s.*